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DYNAMO-ELECTRIC MACHINERY

A MANUAL
FOR STUDENTS OF ELECTROTECHNICS

BY

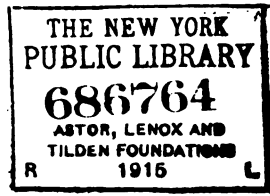
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FIFTH EDITION, REVISED

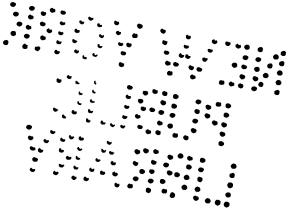
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PREFACE

TO

THE FIFTH EDITION.

SINCE 1892, when the fourth edition of this work appeared, much has been done in the development of the subject, chiefly in the domain of Alternate-current Machinery. To make room for the newer matter the earlier part of the book has been considerably compressed. Much of the chapter relating to the Magnetic Properties of Iron has been transferred to the author's work on *The Electromagnet*. The chapter on Alternators has been rewritten, as has that on Transformers. The subject of Alternate-current Motors has been divided into two parts, the first being now devoted to Synchronous Motors, the second to Asynchronous Motors: but the latter has been briefly handled, owing to the recent publication of the author's work on *Polyphase Electric Currents*, in which polyphase methods, both for generators and for motors, are discussed in detail. The subject of Motor-generators now constitutes a separate chapter.

In a department of applied science which has not only grown so rapidly but has become so highly specialized as this which deals with electric machinery, no single work can adequately treat of all branches. The author therefore refers the reader who desires to follow further any particular branch to the documents to which reference is made in footnotes throughout the book; and also to the books of Ewing on

Magnetic Properties of Iron ; of Fleming on the Alternate-current Transformer ; of Bedell and Crehore on Principles of Alternate Currents ; of Kapp on Transformers, and on the Electric Transmission of Energy ; of Weekes on the Design of Transformers ; and of Du Bois on the Magnetic Circuit.

The author has again to acknowledge his indebtedness to various manufacturers and designers of machines for information and for material for preparing the various drawings. In particular he is under obligations to Messrs. Brown, Boveri and Co. (and to Mr. C. E. L. Brown) ; to the Oerlikon Maschinenfabrik (and to Mr. E. Kolben) ; to Messrs. Mather and Platt (and to Dr. E. Hopkinson) ; to Messrs. Johnson and Phillips ; to Mr. H. F. Parshall, of the British Thomson-Houston Co., of London ; to Mr. Thomas Parker, of Wolverhampton ; to the Crocker-Wheeler Manufacturing Co., of Ampere, N. J. ; to Mr. L. B. Stillwell and to Mr. R. Bellfield, of the Westinghouse Co. ; to Hon. C. A. Parsons ; to Messrs. Siemens and Halske ; to the Allgemeine Elektrizitäts-Gesellschaft ; to Messrs. Pyke and Harris ; to Mr. W. M. Motley, of the Brush Electrical Engineering Co. ; to Mr. W. B. Sayers, and to other engineers too numerous to mention.

A special debt is also acknowledged to M. Boistel, who in translating into French the former edition of this work enriched it with supplementary notices of French forms of machines, of which the author has made use.

Lastly, the author acknowledges the untiring aid he has received throughout the revision from his assistant, Mr. Miles Walker.

S. P. T.

December, 1895.

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DYNAMO-ELECTRIC MACHINERY.

CHAPTER I.

INTRODUCTORY.

A dynamo-electric machine is a machine for converting energy in the form of mechanical power into energy in the form of electric currents, or vice versâ, by magneto-electric induction; the operation being in general that of setting conductors (usually of copper) to rotate in a magnetic field. This definition is framed to include all machines, the action of which is dependent on the principle of induction,¹ discovered by Faraday in 1831.

Every dynamo-electric machine is, however, capable of serving two distinct functions, the converse of one another. When supplied with mechanical power from some external source of power, such as a steam-engine, it furnishes electric currents. When supplied with electric currents from some external source such as a voltaic battery, it furnishes mechanical power. On the one hand the dynamo serves as a

¹ *Induction* means the inducing of electromotive force. The term originated with Faraday himself.

"Then I found that magnets would *induce* just like voltaic currents, and by bringing helices and wires and jackets up to the poles of magnets, electrical currents were *induced* in them These two kinds of *induction* I have distinguished by the term volta-electric and magneto-electric *induction*."—Faraday to R. Phillips, Nov. 1831.

Though Faraday thus fixed the meaning of the term as the *operation* of inducing, a number of recent writers, including Hopkinson, have followed the unfortunate example set by Maxwell in using the term *induction* in a different sense to mean the density of the magnetic flux. This ought to be avoided.

generator, on the other hand as a *motor*. All dynamos, however, belong to one of two great subdivisions, being distinguished, according to the nature of the current which they are to supply, whether *continuous* (i. e. uni-directional in flow) or *alternating* (i. e. rapidly reversing the direction of the flow). We shall therefore have to consider four classes of machines—(a) continuous-current dynamos; (b) alternate-current dynamos, or, briefly, alternators; (c) continuous-current motors; (d) alternate-current motors. In the case of alternate-current machines, there is a further subdivision of classes into those which work with single-phase currents, and those which work with two or three currents in different phases. In general every dynamo, whether intended for use as a generator or as motor, consists of two essential parts, a *field-magnet*, usually a massive, stationary structure of iron surrounded by coils of insulated copper wire, and an *armature*, a peculiarly arranged system of copper conductors, usually wound upon the periphery of a ring, drum, or disk, fixed upon a shaft whereby rotation can be imparted mechanically. There are also special devices for receiving the electric currents from the armature and imparting them to the electric circuit, or *vice versa*, known as *collectors* or *commutators*, attached to the armature and rotating with it, and collecting *brushes*, constituting sliding circuit-connections, which press upon the moving surface of the collector or commutator. In those cases where the collecting brush slides from one piece of metal to another, thereby changing the connections of the circuits, the revolving part is known as the *commutator*. In those cases where there is no change of connections, but merely sliding contact with one and the same piece of metal, the parts are known as *slip-rings* or *collecting-rings*.

The function of the field-magnet is to provide a *magnetic field* of great extent and density; that is to say, to provide a great flux of lines of magnetic force through the space wherein the armature conductors are to revolve. It must consequently consist of a large and well-designed, and therefore powerful, magnet or electromagnet, having its poles so shaped that the magnetic lines that issue from them shall be

utilized in the armature space. The magnetic field and the magnetic properties of iron are dealt with in Chapter VI.; the fundamental principles of the magnetic circuit, including the designing of field-magnets, are dealt with in Chapters VII., VIII. and XVI.

The function of the armature is to rotate in the magnetic field, whilst carrying electric currents in its copper coils or conductors; and, while so rotating, to generate electromotive forces by the operation of "cutting" the magnetic lines. In many modern alternate-current generators the armature is stationary, whilst the magnet revolves. That part ought to be called the armature, which, whether revolving or stationary, is connected to the mains, giving current to them when the machine is used as a generator, or receiving current from them when used as a motor.

It must be remembered that there is a twofold action between a conducting wire (forming part of a circuit) and a magnetic field. *Firstly*, if the conducting wire is forcibly moved across the magnetic field (so as to cut across the magnetic lines), electric currents are generated in the conductor, and a mechanical effort is required to move the conductor. This is the action discovered by Faraday and termed "magneto-electric induction." In every case the induction or generation of currents necessitates the application of mechanical power and the expenditure of energy. This is the principle of the dynamo used as a generator. *Secondly*, if the conducting wire, while situated in the magnetic field, is actually conveying an electric current (from whatever source) it experiences a lateral thrust, tending to move it forcibly, parallel to itself, across the magnetic lines, and so enables it to exert force and to do work. This action, which is the converse of the former, is the principle of the dynamo used as a motor. In the first case power is required to drive the armature; in the second, the armature rotating becomes a source of power. If we have the magnetic field, and supply power to drive the rotating conductor, we get the electric currents; if we have the magnetic field and supply the electric currents to the conductor, it rotates and furnishes power.

Whether the machine be used as generator or as motor, the magnetic field must be present: hence the fundamental consideration in theory is the theory of the magnetic field. As every dynamo will work (at least theoretically) either as generator or as motor, it should be possible to frame a general theory for any machine serving either of these two converse functions. For the sake of simplicity, however, these two functions will be separately considered in the present work.

The mathematical theory of the dynamo is, indeed, complex, and takes different forms for its expression in the various classes of machine now included under the one name of "dynamo." The progress recently made in the theoretical treatment of magnetic problems has simplified matters so much that it is now possible to predict from the construction and dimensions of a dynamo its electrical output under given conditions of speed and load. The theory of alternate-current machines is different in many points from that of machines which are to furnish continuous currents. The theory of the dynamo, then, which will be developed in the present work, will not be a general mathematical theory. The aim will be to deal with physical and experimental rather than mathematical ideas, though of necessity mathematical symbols must be used here as in every kind of engineering work. A physical theory of the dynamo is not new, though none of any great completeness had been given¹ prior to the appearance of the author's lectures at the *Society of Arts* in 1882.

Before, however, proceeding to the general theory of the dynamo, it will be expedient to introduce a few historical notes.

¹ See J. M. Gauguin, *Annales de Chimie et de Physique*, 1873; Antoine Breguet, *Annales de Chimie et de Physique*, 1879; Du Moncel, *Exposé des Applications de l'Électricité*, vol. ii.; Niaudet, *Machines Électriques*; Dreäge's *Electric Illumination*; Schellen, *Die Magneto- und Dynamo-elektrischen Maschinen* (3d edition, 1883).

CHAPTER II.

HISTORICAL NOTES.

FARADAY'S discovery of the magneto-electric induction of currents was made in the autumn of 1831, and communicated, on Nov. 24th, to the Royal Society in a paper printed in the *Philosophical Transactions*, and reprinted in the beginning of the first volume of Faraday's *Experimental Researches in Electricity*. His first experiments related to the production of induced currents in a coil by means of currents started or stopped in a neighboring coil; from these he went on to currents generated in a coil moved in front of the poles of a powerful steel magnet. "Upon thus obtaining electricity from magnets he attempted to construct "a new electrical machine." A disk of copper, 12 inches in diameter (Fig. 1), and about one-fifth of an inch in thickness, fixed upon a brass axle, was mounted in frames, so as to allow of revolution, its edge being at the same time introduced between the magnetic poles of a large compound permanent magnet, the poles being about half an inch apart.¹ The edge of the plate

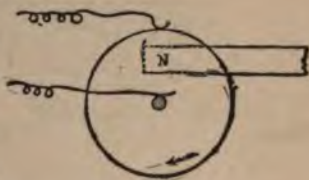


FIG. 1.

FARADAY'S DISK DYNAMO.

was well amalgamated, for the purpose of obtaining a good but movable contact, and a part round the axle was also prepared in a similar manner. Conducting strips of copper and lead, to serve as electric collectors, were prepared, so as to be placed in contact with the edge of the copper disk; one of these was held by hand to touch the edge of the disk between the magnet poles. The wires from a galvanometer were connected, the one to the collecting-strip, the other to the brass axle; then on revolving the disk a deflexion of the galvanometer was obtained, which was reversed in direction when the direction of the rotation was

¹ *Experimental Researches*, i. 25, art. 85. This piece of apparatus is still preserved at the *Royal Institution*. It was shown in action by the author of this work, at a lecture at the Royal Institution delivered April 11th, 1891.

reversed. "Here, therefore, was demonstrated the production of a permanent current of electricity by ordinary magnets." These effects were also obtained from the poles of electromagnets, and from copper helices without iron cores. Several other forms of magneto-electric machines were tried by Faraday.

In one,¹ a flat ring of twelve inches external diameter, and one inch broad, was cut from a thick copper plate, and mounted to revolve between the poles of the magnet, two conductors being applied to make rubbing contact at the inner and outer edge at the part which passed between the magnetic poles. In another,² a disk of copper, one-fifth of an inch thick and only $1\frac{1}{4}$ inch in diameter (Fig. 2), was amalgamated at the edge, and mounted on a copper axle. A square piece of sheet metal had a circular

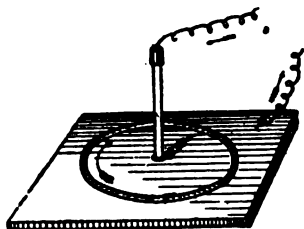


FIG. 2.—FARADAY'S TEETOTUM APPARATUS.

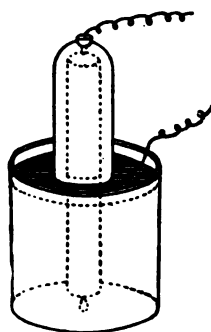


FIG. 3.—FARADAY'S ROTATING COPPER CYLINDER.

hole cut in it, into which the disk fitted loosely, a little mercury completed communication between the disk and its surrounding ring. The latter was connected by wire to a galvanometer; the other wire being connected from the instrument to the end of the axle. Upon rotating the disk in a horizontal plane, currents were obtained though the earth was the only magnet employed.

Faraday also proposed a multiple machine³ having several disks, metallicallly connected alternately at edges and centres by means of mercury, which were then to be revolved alternately in opposite directions. In another apparatus⁴ a copper cylinder (Fig. 3), closed at one extremity, was put over a magnet, one half

¹ *Experimental Researches*, i. art. 135.

² *Ib.*, art. 158.

³ *Ib.*, art. 155.

⁴ *Ib.*, art. 219.

of which it enclosed like a cap, and to which it was attached without making metallic contact. The arrangement was then floated upright in a narrow jar of mercury, so that the lower edge of the copper cap touched the fluid. On rotating the magnet and its attached cap, a current was sent through wires from the mercury to the top of the copper cap. In another apparatus,¹ still preserved at the Royal Institution, a cylindrical bar magnet, half immersed in mercury, was made to rotate, and generated a current, its own metal serving as a conductor. In another form,² the cylindrical magnet was rotated horizontally about its own axis, and was found to generate currents which flowed from the middle to the ends, or *vice versa*, according to the rotation. In

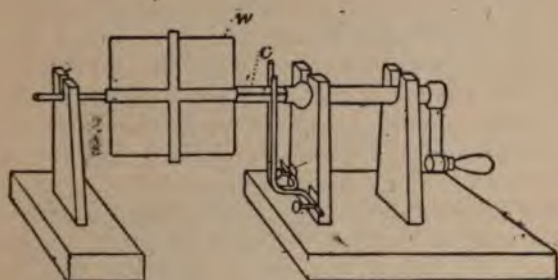


FIG. 4.—FARADAY'S ROTATING RECTANGLE.

all these machines the operations were homopolar, and the induction continuous; but in another machine (Fig. 4) constructed some time later,³ the operation was heteropolar, and the induction alternate. Here a simple rectangle of copper wire, attached to a frame, was rotated about a horizontal axis placed east and west, and generated alternate currents, which could be collected by a simple commutator.

Within a few months machines on the principle of magneto-induction had been devised by Dal Negro,⁴ and by Pixii.⁵ In the latter's apparatus a steel horseshoe magnet, with its poles upwards, was caused to rotate about a vertical shaft, inducing alternate currents in a pair of bobbins fixed above it, and provided with a horseshoe core of soft iron. Later, in 1832, Pixii produced,

¹ *Experimental Researches*, i. art. 220.

² *Ib.*, art. 222.

³ *Ib.*, iii. art. 3192.

⁴ *Phil. Mag.* [3] i. 45, July 1832 (an oscillatory apparatus).

⁵ *Ann. Chim. Phys.*, i. 322, 1832.

at the suggestion of Ampère,¹ a second machine, provided with commutators to rectify the alternating currents. Further improvements were made by Ritchie² and Watkins.³ In 1833 appeared the machine of Saxton,⁴ and two years later that of Clarke;⁵ both having the steel horseshoe magnet a fixture, and having as a revolving armature an electromagnet consisting of a pair of bobbins wound upon a simple horseshoe of iron. Clarke's machine possessed many original details, including a special form of commutator for giving short, sharp currents for physiological purposes. In it the armature rotated, not opposite the ends, but in close proximity to the flat faces of the magnet. In Saxton's machine, which was shown to the British Association at Cambridge in 1833, the armature was rotated opposite the polar ends, and consisted of four coils. Von Ettingshausen,⁶ in 1837, brought out a very similar alternate-current machine, with a special device by which the alternate currents could be cut out. Poggen-dorff,⁷ in 1838, devised a special mercury-cup commutator for Saxton's machine, to make the currents less discontinuous.

Other improvements in detail were made by Petrina,⁸ who improved the commutator; Jacobi,⁹ who pointed out the importance of using short cores for the armatures; Sturgeon,¹⁰ who placed a shuttle-wound coil longitudinally between the limbs of a horseshoe magnet, and who also invented the simple two-part commutator or "unio-directive discharger," as he termed it; Stöhrer,¹¹ who showed how to construct a six-pole machine with six bobbins in the armature; Ritchie,¹² who employed tubular cores and a double winding; and Pulvermacher,¹³ who in 1849 proposed the use of thin laminæ of iron as core-plates. Woolrich,¹⁴ in 1841,

¹ *Ann. Chim. Phys.*, li. 76, 1832.

² *Phil. Mag.* [3] viii. 455; [3] x. 280, 1837; and *Phil. Trans.*, li. 318, 1833.

³ *Phil. Mag.* [3] vii. 107, 1835.

⁴ *Phil. Mag.* [3] ix. 360, 1836.

⁵ *Phil. Mag.* [3] ix. 262, 1836; x. 365, 455, 1837; and Sturgeon's *Annals of Electricity*, i. 145.

⁶ Gehler's *Physikalisches Wörterbuch*, ix. 122, 1838.

⁷ *Pogg. Ann.*, xlv. 385, 1838.

⁸ *Pogg. Ann.*, lxi. 58, 1845.

⁹ *Pogg. Ann.*, lxi. 194, 1846.

¹⁰ *Annals of Electricity*, li. 1, 1838. See, also Sturgeon's *Scientific Researches*, p. 252; also *Phil. Mag.*, vii. 231, 1835.

¹¹ *Pogg. Ann.*, lxi. 417, 1844; lxxvii. 467, 1849.

¹² Specification of Patent, 14,899 of 1849.

¹³ *Loc. cit.*

¹⁴ See also Specification of Patent, 9481 of 1842.

devised a multipolar machine for electroplating, having twice as many rotating coils as magnet-poles. Wheatstone¹ began his improvements in 1841, with a machine in which for the first time the armature coils were so grouped as to give a really continuous current (Fig. 5). For this purpose five armatures, each consisting of a pair of short parallel cylindrical coils with iron cores, and each having a simple split-tube commutator, were arranged in a row along a single shaft, with six compound steel magnets between them, the five armatures being so set that they came

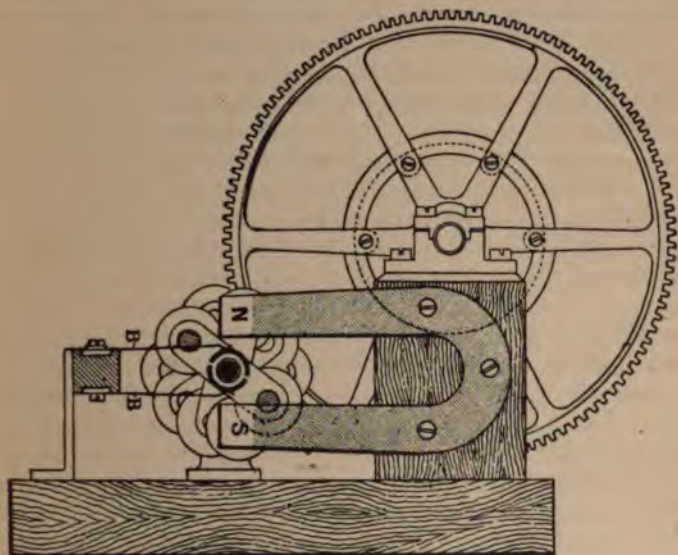


FIG. 5.—WHEATSTONE'S CONTINUOUS-CURRENT MACHINE.

successively into the position of greatest activity, no two of them being commuted at the same instant. They were connected in series with one another by wires, which joined the positive brush—a brass spring—of one to the negative brush of the next. In 1845 Wheatstone² and Cooke patented the use of electromagnets instead of steel permanent magnets in such machines. In 1848 Jacob Brett³ made the important suggestion of causing the current developed in the armature by the permanent magnetism of

¹ Specification of Patent, 9022 of 1841.

² Specification of Patent, 10,655 of 1845.

³ Specification of Patent, 12,054 of 1848.

the field-magnets to be transmitted through a coil of wire surrounding the magnet, so as to increase its action. This suggestion, which appears to be the first indication of the principle of the self-exciting dynamo, was independently made in 1851 by Sinstedden,¹ who appears to have had full knowledge of the fact, investigated by Müller, that steel is capable of receiving a temporary magnetization not greatly inferior to that of wrought iron, and far in excess of that which it can permanently retain. Sinstedden's researches were numerous and important, relating to the best width of polar surface to employ, to the use of pole-pieces, and to the lamination of armature cores, for which purpose he employed, in 1849, iron wire bundles. A quite different type of machine was suggested independently by Ritchie,² by Page,³ and by Du-jardin,⁴ in which neither field-magnet nor armature rotated; the coils in which the currents were to be induced were wound upon polar extensions of the field-magnets, and the induction was produced by rotating in front of them pieces of soft iron, which set up rapid periodic variations in the magnetic field. Machines on this "inductor" principle were later devised by Holmes, Henley, Wheatstone, Wilde, Sawyer, by the author of this work, and by Kingdon.

Nollet,⁵ in 1849, devised an alternate-current machine, in the construction of which he was joined by Van Malderen; and after the death of Nollet this was developed, with the aid, first of Holmes, then of Masson and Du Moncel, into the "Alliance" machine which, from the year 1863, did good service in the light-houses of France. Holmes continued to perfect his work, and produced a fine machine,⁷ which in 1857 received high commendation from Faraday. The great machine of Holmes shown in the International Exhibition of 1862, was a continuous-current machine, with a large commutator and rotating rollers for brushes; the bobbins, 160 in number, were arranged on the peripheries of two wheels, each about 9 feet in diameter. There were

¹ *Pogg. Ann.*, lxxxiv. 186, 1851. For Sinstedden's other researches see *Pogg. Ann.*, lxxvi. 20, 195 and 524, 1849; lxxxiv. 181, 1852; xcii. 1 and 220, 1854; xevi. 353, 1855; cxxxvii. 290 and 483, 1869.

² *Phil. Mag.*, [3] x. 280, 1837. ³ *Annals of Electricity*, 489, 1839.

⁴ *Comptes Rendus*, xviii. 837, 1844; xxi. 528, 892, 1881.

⁵ See Specification of Patent, 13, 302 of 1850. See also Douglass in *Proc. Inst. Civil Engin.*, lvii. 1878-9.

⁶ See Du Moncel's *Exposés des Applications de l'Électricité*, i. 361. Also see Le Roux, *Bulletin de la Société d'Encouragement*, 1868.

⁷ See Douglass, *loc. cit.* Also Specifications of patents, 573 of 1856, 2060 of 1868, and 1774 of 1869.

sixty horseshoe magnets arranged in three circles, each presenting radially forty poles. In 1867 Holmes remodelled his machine, making the field-magnets more powerful in proportion, and leaving the induced currents uncommuted; and in 1869 he introduced the principle of diverting the current from a few of the armature coils, through a commutator, to excite the field-magnets. This period was one of great activity. In 1855 Hjorth¹ patented a remarkable machine, having for its field-magnets a compound arrangement of a permanent magnet to provide initial currents, and powerful electromagnets to be excited up by the currents generated by the machine itself.

C. W. Siemens² in 1856 provisionally patented the famous shuttle-wound longitudinal armature, invented by Werner Siemens. In 1859,³ he made the suggestion that the core only need rotate, the coils being fixed in grooves in the pole-pieces of the field-magnets. Wilde,⁴ of Manchester, embarked on a remarkable series of researches from 1861 to 1867. Beginning with small apparatus for telegraphic purposes, he was led in 1863 to devise an apparatus having a shuttle-wound Siemens armature between the poles of a powerful electromagnet, the coils of which were traversed by currents furnished by a small auxiliary machine—with shuttle-wound armature and permanent magnets—mounted upon its summit. In 1866 and 1867 Wilde devised alternate-current machines, of which the latest had a number of bobbins mounted on the periphery of a disk rotating between two opposite crowns of alternately polarized field-magnets—a type which survives to the present day. These machines, originally separately excited by currents from a small magneto machine, were made self-exciting, in 1873, by diverting through a commutator the currents induced in one or more of the armature bobbins. The principle of using the whole or part of the machine's own currents to excite the requisite magnetism of its field-magnets was by this time becoming recognized. As mentioned above, Brett, Sinsteden, and Hjorth had all made use of his principle. In 1858, Johnson,⁵ patent agent for a foreign inventor,

¹ Specifications of Patents, 12, 205, of 1848, 2199 of 1854, 2198 of 1854, 806 of 1855, 807 of 1855, and 808 of 1855.

² Specification of Patent, 2017 of 1856. See W. Siemens, *Pogg. Ann.*, ci. 271, 1857.

³ Specification of Patent, 512 of 1859.

⁴ Specifications of Patents, 299, 858, 1904 and 2997 of 1861; 516 and 3006 of 1863, 1412 and 2753 of 1865, 3209 of 1866, and 824 of 1867.

⁵ Specification of Patent, 2670 of 1858.

states; "It is proposed to employ the electromagnet in obtaining induced electricity, which supplies wholly or partially the electricity necessary for polarizing the electromagnets, which electricity would otherwise be required to be obtained from batteries or other known sources." In July 1866, Murray¹ stated that he had connected in series with the armature some coils wound on the field-magnets of his magneto machine and recommended the adoption of this plan. In October 1866, Moses G. Farmer² wrote to Wilde of Manchester, describing his success in winding main circuit coils upon the field-magnets of his machine, so as to cause it to excite its own magnets. In November 1866, Baker³ stated that the secondary currents from the revolving magnets might be applied to magnetize the fixed magnets. In December of the same year C. and S. A. Varley⁴ filed a Provisional Specification for a machine having electromagnets only, which apparatus, however, required before using to have given to it a small amount of permanent magnetism since the inventors state that "the bobbins become slightly magnetized in their passage between the poles of the permanent magnets." This, it must be conjectured, was given to it by passing an electric current through the coils of the electromagnets; a device which reappears in another machine patented by the same inventors in June 1867, and again in another by O. and F. H. Varley in 1869. The electromagnets of the 1867 machine were wound with two separate circuits, supplied alternately with currents from two commutators which received the currents from two separate pairs of coils. Mr. S. A. Varley continued, in 1868 and 1871, to patent magneto-electric generators. In 1876 he returned to the self-exciting method, employing a multiple armature in which the principle was applied of cutting out each coil in succession during the rotation. In this machine also there were two windings on the field-magnets, one of greater resistance than the other, both of which were led to the lamp, the circuit of greater resistance being always closed. It was not, however, clear that this method of double winding was what is now understood as "compound winding,"⁵ until such was laid down with legal authority

¹ See *Engineer*, p. 42, July 20, 1866.

² *Proc. Lit. and Phil. Soc. of Manchester*, vi. 107.

³ Specification of Patent, 3039 of 1866.

⁴ Specification of Patent, 3394 of 1866. Other Varley Specifications are 1755 of 1867, 315 of 1868, 131 and 1150 of 1871, 4905 of 1876, 270 and 4435 of 1877, 4100 of 1878.

⁵ See *Phil. Mag.* [4] xlv. 439, 1873.

by a Scotch judge fifteen years later. Returning to the self-exciting principle, we find that on January 17th, 1867, Dr. Werner Siemens¹ described to the Berlin Academy a machine for generating electric currents by the application of mechanical power, the currents being induced in the coils of a rotating armature by the action of electromagnets, which were themselves excited by the currents so generated. In this machine also initial permanent magnetism was to be given by sending a preliminary current through the coils from a battery. To mark the importance of this departure Siemens coined the name *dynamo-electric machine*, which now, in the shortened form of *dynamo*, has become the

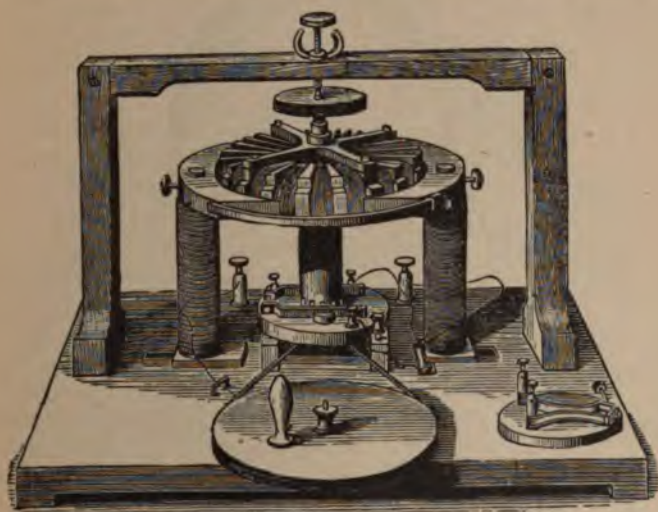


FIG. 6.—PACINOTTI'S MACHINE, WITH RING ARMATURE.

familiar term for all these electric machines driven by mechanical power, whether self-excited or not. On the same day that this discovery was announced to the Royal Society, February 14th, 1867, a paper was read by Sir C. Wheatstone,² making an almost identical suggestion; but with this difference, that whilst Siemens proposed that the exciting coils should be in the main circuit, in series with the armature coils, Wheatstone proposed that they should be connected as a shunt. A self-exciting machine without permanent magnets had indeed been constructed

¹ *Berliner Berichte*, Jan. 1867; *Proc. Roy. Soc.*, Feb. 14, 1867; Specification of Patent, 261 of 1867; and *Pogg. Ann.*, cxxx. 332, 1867.

² *Proc. Roy. Soc.*, Feb. 14, 1867.

for Wheatstone by Mr. Stroh in the summer of 1866. In 1867 Ladd¹ exhibited a self-exciting machine having two shuttle-wound armatures, a small one to excite the common field-magnet, a large one to supply currents for electric light.

Meantime the question of procuring continuous currents, with less fluctuation in their strength, had come up, and had received from Pacinotti² an answer which, though it fell into temporary oblivion, is now recognized as of great merit. He devised a machine, first described in 1864, having as its armature an elec-

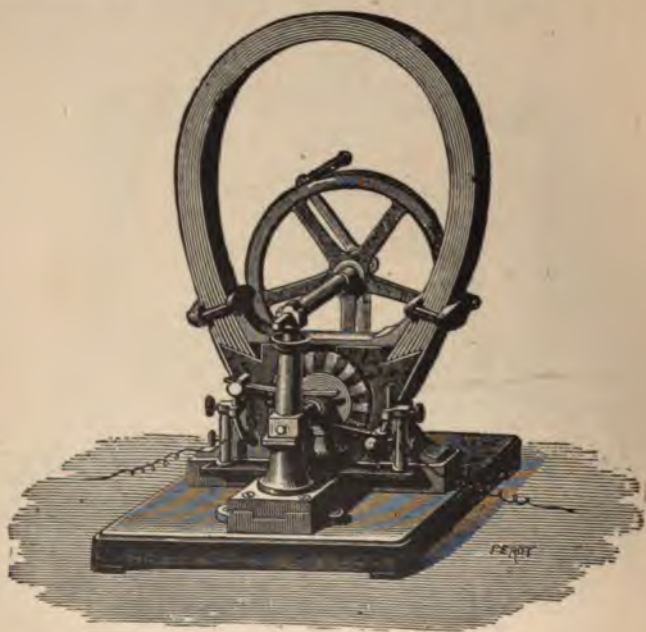


FIG. 7.—GRAMME MACHINE, LABORATORY PATTERN.

tromagnet in the form of a ring, the core consisting of a toothed iron wheel, between the teeth of which the coils were wound in sixteen separate sections. He denominated this a "transversal electromagnet." The coils being joined up in a closed circuit, if at any point a current was introduced, it flowed both ways through the coils to some other point where it was taken off by a return wire. By the device of leading down connections, at sixteen dif-

¹ *Phil. Mag.* [4] xxxiii. 544, 1867.

² *Nuovo Cimento*, xix. 378, 1865.

ferent points around the ring, to sixteen insulated pieces of metal arranged as a commutator, it was possible to cause magnetic poles to appear in the ring at any desired points. The principle of winding a continuous coil in separate symmetrical sections around a ring, or other figure of revolution, was independently invented, in 1870, by Gramme,¹ whose ring had no teeth, and was entirely overwound with wire. By winding an armature with a number of such symmetrically grouped coils which pass successively through the magnetic field, currents can be obtained that are practically steady. The introduction of the Gramme armature was at once recognized as marking an important step, and it gave

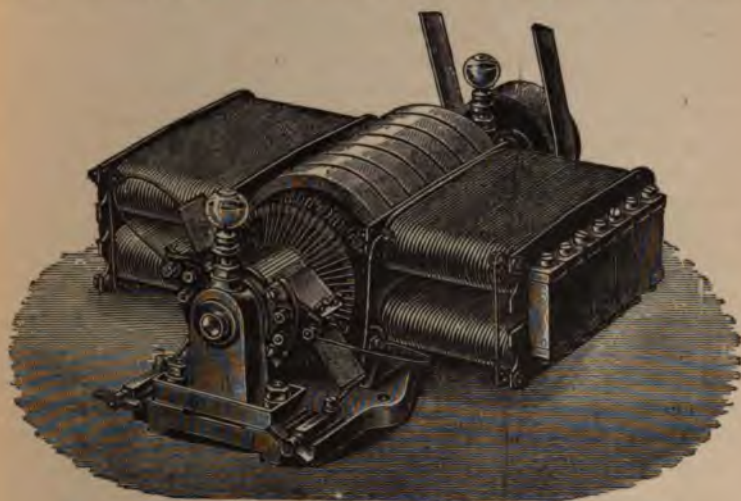


FIG. 8.—SIEMENS'S DYNAMO WITH VON HEFNER ALTENECK'S DRUM-WOUND ARMATURE.

a fresh impetus to invention. In 1873 von Hefner Alteneck² modified the longitudinal armature of Siemens by covering it with windings spaced out at symmetrical angles to secure the same advantage of continuity, and Lontin³ in 1874 sought to perform a like transformation upon an armature with radiating poles. Gramme and Siemens both devised many special forms of machines, some

¹ *Comptes Rendus*, lxxiii. 175, 1871, and lxxv. 1497, 1872; and Specification of Patent, 1668 of 1870.

² Specification of Patent, 2006 of 1873. A similar suggestion had been thrown out the previous year by Worms de Romilly.

³ Specifications of Patents 473 of 1875, 386 and 3264 of 1876.

furnishing alternating currents,¹ others continuous currents. Bertin in 1875, Brush in 1879, and Siemens,² in 1880, revived the method of shunt-winding.

In 1878 Pacinotti³ devised a kind of armature in which the conductors took the form of a flat disk or fly-wheel. Brush⁴ also introduced his famous dynamo embodying the principle of open-coil working. He also introduced the simultaneous use of a shunt and a series winding for the purpose of enabling the machine to do either a large or a small amount of work. Another open-coil machine was introduced in 1880 by Elihu Thomson and E. J. Houston,⁵ of Philadelphia. About the same time Weston⁶ devised several forms of dynamo, and in particular developed shunt-wound machines. Many other American inventors produced dynamos, amongst them Edison,⁷ who began in 1878, with a machine in which the motion was oscillatory instead of rotatory, a device which had been tried by Dujardin,⁸ in 1856, by Siemens,⁹ in 1859, by Wilde,¹⁰ in 1861, and abandoned. Edison himself abandoned it in 1879 for a form of machine having a modified Hefner-Alteneck armature and an elongated shunt-wound electro-magnet. In 1881 he produced a disk dynamo on the same lines as Pacinotti's disk. The same year saw a revival of alternate-current machines in the forms devised by Lord Kelvin¹¹ (and independently by Ferranti) and Gordon,¹² who constructed large two-phase generators.

About this time multipolar dynamos began to come into favour, the multipolar drum armature introduced by Lord Elphinstone¹³ and Mr. Vincent, and the multipolar ring, independently, by Schuckert, Gramme, Gülcher, and Mordey.¹⁴ Lord Elphinstone in particular drew attention to the importance of perfecting the magnetic circuit, though, for purely mechanical reasons, his machine

¹ Specifications of Patents, Gramme, 953 of 1878; Siemens, 3134 of 1878.

² *Phil. Trans.*, March 1880.

³ *Nuovo Cimento* [3] i. 1881.

⁴ Specification of Patent, 2003 of 1878.

⁵ Specification of Patent, 315 of 1880.

⁶ Specifications of Patents, 4280 of 1876, 1614 and 2194 of 1882.

⁷ Specifications of Patents, 4226 of 1878, 2402 of 1879, 1240 and 2054 of 1881, and 2052 of 1882.

⁸ See Du Moncel's *Exposé des Applications*, i. p. 372.

⁹ Specification of Patent, 512 of 1859.

¹⁰ Specification of Patent, 924 of 1861.

¹¹ Specification of Patent, 5668 of 1881.

¹² Specifications of Patents, 5536 of 1881 and 2871 of 1882.

¹³ Specifications of Patents, 332 of 1879, and 2893 of 1880.

¹⁴ Specification of Patent, 400 of 1883.

soon became obsolete. Hopkinson¹ showed how greatly the performance of a dynamo was improved by improving and making more compact its magnetic circuit, whilst Crompton² amidst a number of improvements in detail, showed the advantage of increasing the cross-section of iron in the armature core. Meantime theoretical considerations had led Marcel Deprez,³ in 1881, to the conclusion that a dynamo driven at a certain critical speed ought to be able to distribute currents at a constant potential if its field-magnets were provided with a second coil to furnish from a battery or other source an independent and constant auxiliary excitation. This was almost immediately followed by the general adoption of the so-called compound winding, for the purpose of obtaining a self-regulating dynamo, this advance being the subject of conflicting rival claims. Since 1883 the chief progress made has been in details of design and mechanical construction. Large multipolar machines for continuous currents have been designed by Siemens and Halske, by C. E. L. Brown, and others, and are superseding bipolar forms. Disk dynamos have also been introduced by Desroziers and by Fritsche. Special methods of construction to facilitate the sparkless collection of large currents have been devised by Ryan and by W. B. Sayers. Large alternating machines have been constructed by various designers, Mordey's machine having a notable departure in the use of a single compact magnetic circuit for the field-magnet. Polyphase alternate-current generators have been introduced, chiefly since 1891, for the purpose of furnishing two or more alternate currents differing in phase from one another; the reason for these machines being the convenience of distributing power by alternate currents to polyphase motors. Quite recently there are signs of a revival of the "inductor" type of alternator, having no copper in the moving parts; Kingdon, Stanley, Brown, Dobrowolsky, Pyke and Thury having independently perfected such machines. The "umbrella type of dynamo, with vertical driving shaft was introduced by Brown for turbine service, and has been used in many very large machines. The largest are the two-phase alternators in use at Niagara, constructed by the Westinghouse Co.

The other branch of the subject, that of the electric motor, goes back to the discovery by Faraday⁴ in 1821 of electromagnetic rota-

¹ Specification of Patent, 973 of 1883.

² Specifications of Patents, 2618 and 4810 of 1882, and 4302 of 1884.

³ *La Lumière Électrique*, December 3, 1881, and January 5, 1884.

⁴ *Journal of Royal Institution*, September 1821.

tion, and the invention, in 1823, by Barlow,¹ of his rotating wheel. The earliest electric motors in which the principle of attraction by an electromagnet was applied were those of Henry,² in 1831, and of Dal Negro,³ in 1832, and these were followed in 1833 and 1834 by the motors of Ritchie⁴ and of Jacobi,⁵ and in 1837 by that of Davenport.⁶ Many other inventors devised machines of this kind, some of the most famous being Page⁷ in the United States, Davidson in Scotland, Wheatstone⁸ in England, Froment⁹ in France, and Pacinotti¹⁰ in Italy. The discovery that the action of a dynamo is the simple converse of that of the motor, and that the same machine can serve either function, appears to have been made by Lenz,¹¹ in 1838. It was known to Jacobi¹² in 1850, though it only came into general recognition somewhat later. It was certainly known in 1852, for in the fourth edition of Davis's *Magnetism*, published at Boston, an apparatus, described as a "revolving electro-magnet" (a slight modification of Ritchie's motor) is shown, on page 212, as a motor, and the same apparatus is again shown on page 268 as a generator, accompanied by the remark that "any of the electromagnetic instruments in which motion is produced by the mutual action between a galvanic current and a steel magnet may be made to afford a magneto-electric current by producing the motion mechanically." Walenn¹³ explicitly stated the same point in 1860; and it was also stated by Pacinotti in 1864. The principle of transmitting power from one dynamo used as a generator to another used as a motor is claimed for Fontaine and Gramme, as a discovery made in 1873, when such an arrangement was shown at Vienna. It has been noisily claimed, but without the shadow of reason, for Marcel Deprez,¹⁴ who did not, however, discover it until 1881. In 1882 Ayerton

¹ Barlow, *On Magnetic Attraction* (1823), 279; and *Encyclopædia Metropolitana* (1824), iv. art. *Electromagnetism*, 36.

² *Silliman's Journal*, xx. 340, 1831. Also Henry, *Scientific Writings* (1886), i. 54. ³ *Annali delle Scienze Lombardo-Veneto*, March 1834.

⁴ *Phil. Trans.*, 1833 [2], 318.

⁵ *L'Institut*, lxxxii. Dec. 1834.

⁶ See *Annals of Electricity*, ii. 1838; *Encyclopædia Britannica* (ed. vii.) art. *Voltaic Electricity*, 687.

⁷ *Silliman's Journal*, xxxiii. 178; and [2] x. 344 and 483, 1850.

⁸ Specification of Patent, 9022 of 1841.

⁹ See *Cosmos*, x. 495, 1857, and *La Lumière Electrique*, ix. 193, June 1883.

¹⁰ *Nuovo Cimento*, xix. 378, 1865.

¹¹ See Sturgeon's *Annals of Electricity*, iii. 384, 1838; and *Pogg. Ann.*, xxxi. 483, 1838. ¹² *Mémoire sur la Théorie des Machines électromagnétiques*.

¹³ Specification of Patent, 2587 of 1860.

¹⁴ Specification of Patent, 2830 of 1882. See *Journ. Soc. Electr. Engineers*, xii. 301, 1883.

and Perry made the important discovery of the automatic regulation of motors, to run with constant velocity, by methods akin to, but the converse of, those adapted for making dynamos self-regulating. Since that date, the improvements made in continuous current motors, though great, have been in mechanical perfection of design and detail. The alternate-current dynamo does not make a convenient alternate-current motor, as it is not self-starting. When once started, however, it runs in absolute synchronism with the generator. Bailey, in 1879, showed how to produce rotation by the currents induced in a copper disk placed in a systematically shifting magnetic field. Ferraris, in 1888, made the important suggestion to drive a motor by two independent alternate currents of similar period, but differing in phase, thus producing a rotating magnetic field. The same suggestion came independently from Nikola Tesla, who first put such motors into practical form. Many forms of rotatory-field motors have since been devised; various engineers, including Dolivo-Dobrowolsky, C. E. L. Brown and others, have brought the induction motor to a remarkable pitch of perfection. In the States a two-phase motor on a different plan has been perfected by Stanley and Kelly. The success of these polyphase motors, in which the rotating part is an entirely independent simple structure of iron and copper, receiving its currents by induction and without any commutator or circuit connections, has led to the device of single-phase motors for use with simple alternate currents. The structure of these motors resembles that of the polyphase motors, since the revolving part receives its currents solely by induction.

The theory of the dynamo dates back to the investigations of Weber¹ and of Neumann² respecting the general laws of magneto-electric induction, followed by Jacobi's³ calculations and experiments respecting the performance of an electric motor, by Pogendorff's⁴ and Koosen's⁵ investigations of the theory of the Saxton magneto machine, and by the researches of Lenz,⁶ Joule,⁷ Le Roux,⁸ and of Sinstedden.⁹ These researches were followed at a

¹ *Elektrodynamische Maasbestimmungen* (1846).

² *Berliner Berichte*, p. 1, 1845; and p. 1, 1847.

³ *Pogg. Ann.*, li. 370, 1840; lxix. 181, 1846; and *Krönig's Journal*, iii. 377, 1851. Also *Ann. Chim. Phys.* [3] xxxiv. 451, 1852.

⁴ *Pogg. Ann.*, xlv. 390, 1838.

⁵ *Pogg. Ann.*, lxxxv. 226; and lxxxvii. 386, 1852.

⁶ *Pogg. Ann.*, xxi. 483, 1834; xxxiv. 385, 1835; and xcii. 128, 1854.

⁷ *Annals of Electricity*, iv. v. 1839-40; *Phil. Mag.* [3] xxlii. 263, 347 and 435, 1843.

⁸ *A. Chim. Phys.* [3] l. 463, 1857. ⁹ *Pogg. Ann.* lxxxiv. 181, 1851.

long interval by those of Favre,¹ followed by silence for twenty years, broken only by the pregnant, but almost totally forgotten, little paper in which Clerk-Maxwell² laid down a theory for self-exciting machines. On the revival of electric lighting the theory of the dynamo was again studied, important contributions being made by Mascart,³ Hagenbach,⁴ von Waltenhofen,⁵ Hopkinson,⁶ Herwig,⁷ Meyer⁸ and Auerbach,⁹ and Joubert. The latter founded the modern theory of alternate-current machines. Hopkinson¹⁰ devised the method of representing, by a curve, the relation between the current and the working electromotive-force of the machine; such curves, under the name of "characteristics," subsequently formed the basis of the theoretical researches of Marcel Deprez.¹¹ In 1880 Frölich¹² began a series of investigations, both experimental and theoretical, that led to equations of remarkable simplicity, if not of more than approximate value, and in 1883 Clausius,¹³ adopting Frölich's fundamental expression for the law of the electromagnet, evolved with great elaboration a theory in which all the various secondary effects arising in generators were taken into account—a theory which he later extended to the case of motors. In 1886 John and Edward Hopkinson¹⁴ published a remarkable paper, developing, from theoretical considerations respecting the induction of magnetism in a magnetic circuit of given form and materials, a theory of the dynamo, the perfection of which may be judged by the fact that its use, as now extended by various workers, enables the performance of a machine to be predicted with extraordinary accuracy from the design as laid down in the working drawings. Other contributions to the theory of dynamos have been made by Lord Kelvin¹⁵. (windings to secure

¹ *Comptes Rendus*, xxxiv. 342, 1853; xxxix. 1212, 1854; xlv. 337, 658, 1858.

² *Proc. Royal Soc.*, Mar. 14, 1867; and *Phil. Mag.* [4] xxxiii. [474], 1867.

³ *Journal de Physique*, vi. 204, 297, 1877; and vii. 89, 1878.

⁴ *Archives des Sciences Physiques*, lv. 255, March 1876; and *Pogg. Ann.*, clviii. 599, 1876.

⁵ *Wiener Berichte*, lxxx. 601, 1879.

⁶ *Proc. Inst. Mech. Engineers*, 238, 1879, and 266, 1880.

⁷ *Wied. Ann.*, viii. 494, 1880.

⁸ *Wied. Ann.*, viii. 494, 1879.

⁹ *Ann. de l'Ecole Normale*, x. 131, 1881; and *Journal de Physique* [2] ii. 293, 1883.

¹⁰ *Proc. Inst. Mech. Engineers*, 238, 1879.

¹¹ *Comptes Rendus*, xcii. 1152, 1881; and *La Lumière Electrique*, xv. 1, 1885.

¹² *Berl. Berichte*, 962, 1880; *Electrotechnische Zeitschrift*, ii. 134, 170, 1881; vi. 128, etc., 1885; and ix., Nov. 1888.

¹³ *Wied. Ann.*, xx. 353, 1883; xxi. 385, 1884; *Phil. Mag.* [5] xvii. 49 and 119, 1884.

¹⁴ *Phil. Trans.*, i. 331, 1886.

¹⁵ *Journal de Physique* [2] ii. 240, 1887; and *Comptes Rendus*, xciii. 474, 1881.

maximum efficiency), Kapp¹ (pre-determination of characteristic curve), Rücker² (limits of self-regulation), Esson³ (design of multipolar machines), and others. Hering,⁴ Fritsche,⁵ and Arnold⁶ have published studies on the modes of winding armatures; and the latter has given a formula for all kinds of continuous-current machines with closed-coil armatures. Methods of analyzing the various losses of energy due to friction, hysteresis and eddy-currents have been devised by Mordey,⁷ and later by Kapp⁸ and Housman,⁹ independently. The theory of alternate current motors both of the asynchronous and of the synchronous types has of late received much attention from various writers.¹⁰

¹ *Journ. Soc. Electr. Engineers*, xv. 518, 1887.

² *Phil. Mag.* (5) xix., 462, June 1885.

³ *Journal Inst. Electrical Engineers*, xx. 1891.

⁴ Hering's *Principles of Dynamo-electric Machines*, New York, 1880.

⁵ Fritsche's *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

⁶ Arnold's *Die Ankerwicklung der Gleichstrom-Dynamomaschinen*, Berlin, 1891.

⁷ *Journal Inst. Electrical Engineers*, xviii. 620, 1889.

⁸ *Electrician*, xxvi. 700, 1891.

⁹ *Ib.*; see also *Journal Inst. Electrical Engineers*, xx. 303, 1891.

¹⁰ Ferraris, "Rotazioni elettrodinamiche," *Turin Acad.*, March 1888.

L. Duncan, "Alternate Current Motors," *Elec. World* (N. Y.), xvii. 341, 357.

Hutin and Leblanc, *La Lumière Électrique*, xl. 373.

Dr. J. Sahulka, *Ueber Wechselstrom-Motoren*, Leipzig, 1892.

R. V. Picou, *Les Moteurs Électriques à champ magnétique tournant*, Paris, 1892.

E. Arnold, *Theorie und Berechnung der asynchronen Wechselstrom-Motoren*; and see articles by same author in *Elec. World* (N. Y.), 1893-4.

G. Ferraris, "A Method for the Treatment of Rotating or Alternating Vectors, &c.," *Electrician*, 1894, xxxiii. 110, 129, 152, 184.

Reber, "Two- and Three-phase Motors," *Amer. Inst. Elec. Eng.*, October 1894.

Steinmetz, *Amer. Inst. Elec. Engineers*, December 1894, p. 803.

A. Potier, "Sur les Moteurs à induit fermé sur lui-même," *Bull. de la Soc. Internationale des Électriciens*, May 1894, 248.

De Bast, *Bull. de l'Assoc. des Ingénieurs Électriciens*, Aug. 1893.

Dr. J. Hopkinson, "On the Theory of Alternating Currents, particularly in reference to Two Alternate-Current Machines connected to the same Circuit," *Journ. Soc. Teleg. Engineers*, xiii. 496, 1884.

W. M. Mordey, "On Parallel Working, with special reference to Long Lines," *Inst. of Elec. Engineers*, xiii. 260, 1894.

Blondel, "Couplage des Alternateurs," *La Lumière Elec.*, xlv. 351, 1892.

Steinmetz, "Theory of a Synchronous Motor," *Amer. Inst. Elec. Engineers*, Oct. 17, 1894.

Picou, "Transmission de Force par Moteurs Alternatifs Synchrones," *Soc. Internationale des Électriciens*, Feb. 1895.

Bedell and Ryan, "Action of a Single-Phase Synchronous Motor," *Journ. Franklin Inst.*, March 1895.

Rhodes, "Theory of the Synchronous Motor," *Proc. Physical Society*, 1895.

CHAPTER III.

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES.

ALL dynamos are based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. Faraday's principle may be enunciated as follows :—When a conductor is moved in a magnetic field so as to cut the lines of force, there is an electromotive-force induced in the conductor, in a direction at right angles to the direction of the motion, and at right angles also to the direction of the lines of force.

Dr. Fleming has given a most useful rule for remembering this connection between motion, magnetism, and induced electromotive-force. Hold the thumb and the first and middle fingers of the right hand as nearly as possible at right angles to each other, as in Fig. 9, so as to represent three rectangular axes in space. If the thumb point in the direction of the motion, and the forefinger point along the direction of the magnetic lines, then the middle finger will point in the direction of the induced electromotive-force.¹

This induced electromotive-force is, as Faraday showed, proportional to the number ² of magnetic lines cut per second ; and is, therefore, proportional to the density of the magnetic field, and to the length and velocity ³ of the moving conductor.

¹ A more usual rule for remembering the direction of the induced currents is the following adaptation from Ampère's well known rule :—Supposing a figure swimming in any conductor to turn so as to look along the (positive direction of the) lines of force. Then if he and the conductor be moved towards his right hand, he will be swimming with the current induced by this motion.

² For the numerical signification to be attached to the term "number of magnetic lines," see p. 113.

³ If the direction of the motion is not at right angles to the direction of the field, the resolved part of the velocity in the direction at right angles to the field must be considered as the effective velocity.

For steady currents, the flow of electricity in the conductor is, by Ohm's well-known law, directly proportional to this electromotive force, and inversely proportional to the resistance of the conductor. For sudden currents, or currents whose strength is varying rapidly, this is no longer true. And it is one of the most important matters, though one too often overlooked in the construction of dynamo-electric machinery, that the "resistance" of a coil of wire, or of a circuit, is by no means the only obstacle offered to the generation of a momen-

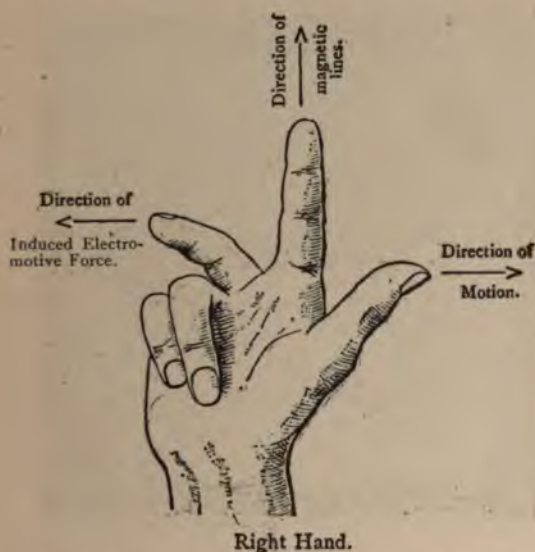


FIG. 9.—ILLUSTRATION OF FLEMING'S RULE.

tary current in that coil or circuit; but that, on the contrary, the "self-induction" exercised by one part of a coil or circuit upon another part or parts of the same, is a consideration, in many cases quite as important as, and in some cases more important than, the resistance.

To understand clearly Faraday's principle—that is to say, how it is that the act of moving a wire so as to cut magnetic lines of force can induce or generate a current of electricity in that wire—let us inquire what a current of electricity is.

A wire through which a current of electricity is flowing looks in no way different from any other wire. No man has ever yet seen the electricity running along in a wire, or knows precisely what is happening there. Indeed, it is still a disputed point which way the electricity flows, or whether or not there are two currents flowing simultaneously in opposite directions. One thing is certain: that the energy does not flow along the substance of the wire at all, but is transmitted across the surrounding medium, transversely. Until we know

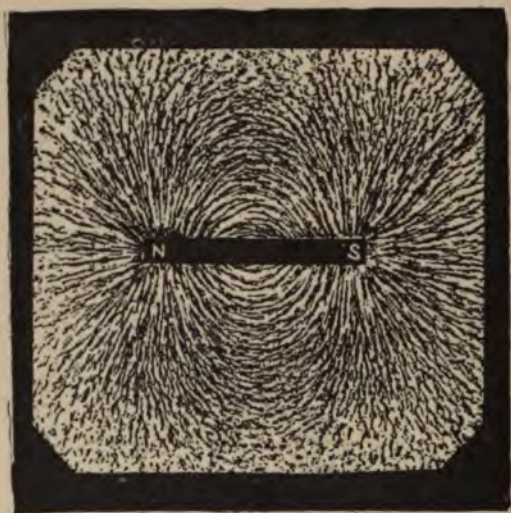


FIG. 10—MAGNETIC FIELD OF BAR-MAGNET.

with absolute certainty what electricity is, we cannot expect to know precisely what a current of electricity is. But no electrician is in any doubt as to one most vital matter, namely, that when that which is called an electric current flows through a wire, the magnetic forces with which that wire is thereby, for the time, endowed, reside not in the wire at all, but in the space surrounding it. Every one knows that in the space or "field" surrounding a magnet there are magnetic forces whose direction and intensity are conveniently portrayed by magnetic "lines of force." These lines start in

tufts from the N-pointing pole and curve round to the S-pointing pole of the magnet. They are invisible until, by dusting iron filings into the field, their presence is made known, though they are always in reality there (Fig. 10), and can be detected in several independent ways. A view of the magnetic field at the pole of a bar magnet, as seen end on, would, of course, exhibit merely radial lines, as seen in Fig. 11.

Now, every electric current (so called) is surrounded by a magnetic field, the lines of which can be similarly revealed.



FIG. 11.—MAGNETIC FIELD ROUND ONE POLE, END-ON.

To observe them, a hole is bored through a card or a piece of glass, and the wire which carries the current must be passed up through the hole. When iron filings are dusted into the field they assume the form of concentric circles (Fig. 12), showing that the lines of force run completely round the wire and do not stand out in tufts. In fact, every conducting wire is surrounded by a sort of magnetic whirl, like that shown in Fig. 13. A great part of the energy of the so-called electric current in the wire consists in these external magnetic whirls. To set them up requires an expenditure of energy; the current

on being started does not instantly assume its full strength, part of its energy is being employed during the variable period in building up this surrounding field. On stopping the current by breaking the circuit this surrounding energy returns back into the circuit, the field, as it collapses upon the wire, tending to maintain the current, and causes the spark seen at the break of the circuit. It is these magnetic whirls which act on

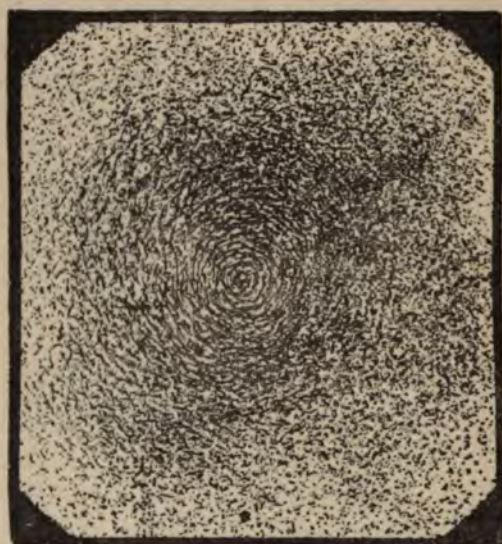


FIG. 12.—MAGNETIC FIELD SURROUNDING CURRENT. THE CONDUCTING WIRE SEEN END-ON.

magnets, and cause them to set, as galvanometer needles do, at right angles to the conducting wire.

Now, Faraday's principle of induction is nothing more or less than this :—That by moving a wire near a magnet, across a space in which there are magnetic lines, the motion of the wire, as it cuts across those magnetic lines, sets up magnetic whirls round the moving wire, or, in other language, generates a so-called current of electricity in that wire. Poking a magnet pole into a loop or circuit of wire also necessarily enerates a momentary current in the wire loop, because it

momentarily sets up magnetic whirls. In Faraday's language, this action increases the number of magnetic lines embraced by the circuit.

It is, however, necessary that the moving conductor should, in its motion, so cut the magnetic field as to alter the number of magnetic lines that pass through the circuit of which the moving conductor forms part. Without a variation in the magnetic flux that penetrates the circuit there will be no induction. An induction will always occur in any circuit when any change in the flux takes place, however that change may be produced. If a conducting circuit—a wire ring or single coil, for example—be moved along in a uniform magnetic field, as indicated in Fig. 14, so that only the same lines of force pass through it, no current will be generated. Or if, again, as in Fig. 15, the coil be moved by a motion of translation to another part of the uniform field, as many lines of force will be left behind as are gained in advancing from its first to its second position, and there will be no current generated in the coil: the flux of magnetic lines has not varied. If the coil be merely rotated on itself round a central

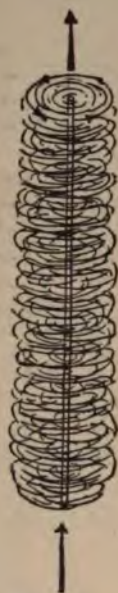


FIG. 13.
MAGNETIC WHIRL
SURROUNDING
WIRE CARRYING
CURRENT.

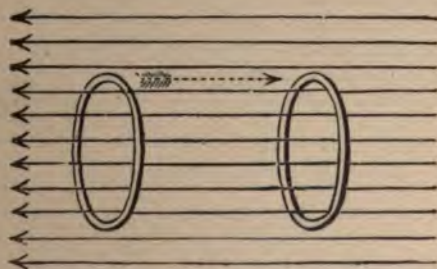


FIG. 14.—CIRCUIT MOVED WITHOUT CUTTING LINES OF FORCE OF
A UNIFORM MAGNETIC FIELD.

axis, like the rim of a fly-wheel, it will not cut any more lines of force than before, and this motion will generate no current. But if, as in Fig. 16, the coil be tilted in its motion across the uniform field, or rotated round any axis in its own plane, then

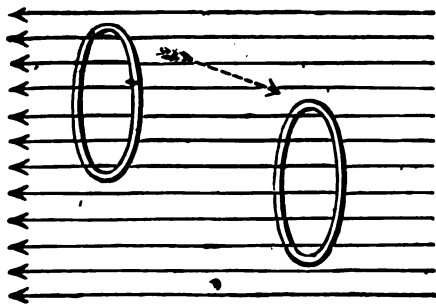


FIG. 15.—CIRCUIT MOVED WITHOUT CUTTING ANY MORE LINES OF FORCE.

the number of magnetic lines that traverse it will be altered and currents will be generated. These currents will flow round the ring coil in the right-handed direction (as viewed

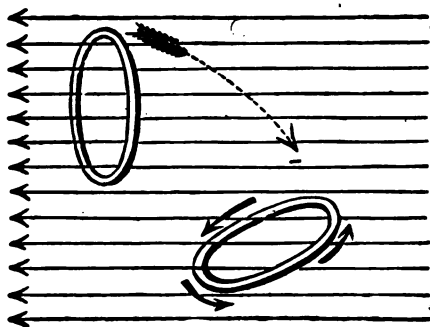


FIG. 16.—CIRCUIT MOVED SO AS TO ALTER NUMBER OF LINES OF FORCE THROUGH IT.

by a person looking along the magnetic field in the direction in which the magnetic lines run), if the effect of the movement is to diminish the number of lines of force that cross the coil; they will flow round in the opposite sense if the effect of the

movement is to increase the number of intercepted lines of force.

If the magnetic field be not a uniform one, then the effect of taking the coil by a simple motion of translation from a place where the lines of force are dense to a place where they are less dense, as from position 1 to position 2 in Fig. 17, will be to generate currents. Or, if the motion be to a place where the lines of force run in the reverse direction,¹ the effect will be the same, but even more powerful.

In the process called *homopolar* or "unipolar" induction (Chap. XIX.), conductors with sliding contacts move continuously through a uniform field; there being no reversals.

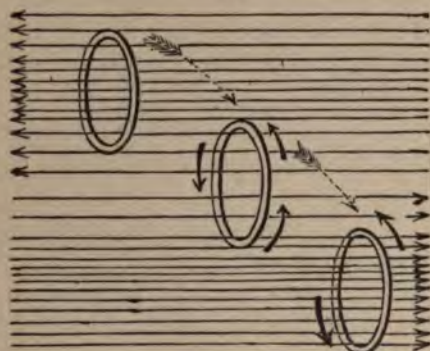


FIG. 17.—MOTION OF CIRCUIT IN NON-UNIFORM MAGNETIC FIELD.

We may now summarize the points under consideration and some of their immediate consequences, in the following manner:—

(1) To induce currents in a conductor there must be relative motion between conductor and magnet, of such a kind as to alter the number of magnetic lines embraced in or enclosed by the circuit.

(2) Increase in the number of magnetic lines embraced by the circuit generates an electromotive-force in the opposite sense to that induced by a decrease.

¹ As a matter of fact, it would be impossible to have a magnetic field exactly like Fig. 17; for in the intermediate part, between the upper and lower fields, the magnetic lines would be of curved complex form.

(3) The more powerful the magnet pole or magnetic field, the higher will be the electromotive-force generated.

(4) The more rapid the motion, the higher will be the electromotive-force.

(5) By joining in series a number of such moving conductors, the electromotive-forces in the separate parts are added together; hence very high electromotive-forces can be obtained by using numerous coils properly connected.

(6) Since the quantity or strength of the current depends on the resistance of the conductors in the circuit, as well as on the electromotive-force, all unnecessary resistance should be avoided.

(7) The number of magnetic lines being finite, the process of a generating machine in alternately increasing and diminishing the flux enclosed by the moving conductor must necessarily generate currents alternate in direction.

(8) By using a suitable commutator, all the currents, direct or inverse, induced during recession or approach, can be turned into the same direction in the wire that goes to supply currents to the external circuits; and if the rotating coils are properly grouped so that before the electromotive force in one set has died down another set is coming into action, then it will be possible, by using an appropriate commutator, to combine their separate currents into one practically uniform continuous current.

(9) As induction depends upon the relative motion of conductor and magnetic lines, it is a mere question of mechanical convenience whether the magnet be stationary while the copper conductor moves, or whether the conductor is fixed while the magnet moves.

(10) To the conductor which is generating the electromotive-force by cutting the magnetic lines, it makes no difference what the origin of those lines is, whether from a permanent magnet of steel or from an electromagnet, provided the number of magnetic lines so cut is the same.

(11) To the moving conductor it makes no difference what the origin of the motion is. Whether the motion be due

to a steam-engine, or to a gas-engine, or to hand-driving, or to driving by means of an electric current in the wire itself (as in the case of electric motors), it makes no difference to the moving conductor, which, provided the speed and the number of magnetic lines to be cut are given, will generate the same electromotive-force.

To make more clear the considerations which will occupy us when discussing individual types of dynamo, we will first examine some fundamental points in the general mechanism and design of dynamo machines. We will deal with the various matters in order, beginning with the various organs or parts of the machine. Having discussed these, we take up the nature of the processes that go on in the machine when it is at work, the action of the magnetic field on the rotating armature, the reactions of the armature upon the field in which it rotates. We must then enter upon the magnetic part of the subject, and discuss the magnetic properties of iron so far as is needed for the purpose of dynamo design. We shall then consider the design of field-magnets, and the design and construction of armatures.

ORGANS OF DYNAMO-ELECTRIC MACHINES.

The simplest conceivable dynamo is that sketched in Fig. 18, consisting of a single rectangular loop of wire rotating in a simple and uniform magnetic field between the poles of a large magnet. If the loop be placed at first in the vertical plane, the number of lines that pass through it from right to left will be a maximum, and as it is turned into the horizontal position the number diminishes to zero; but on continuing the rotation the lines begin again to penetrate the loop from the opposite side, so that there is a negative maximum when the loop has been turned through 180° . During the half-revolution, therefore, currents will have been induced in the loop, and these currents will be in the direction from back to front in the part of the loop which is rising on the left, and in the opposite direction, namely, from front to back, in that

part which is descending on the right. On passing the 180° position, there will begin an induction in the first sense, for now the number of negative lines of force is diminishing, which is equivalent to a positive increase in the number of lines of force: and this increase would go on until the loop reached its original position, having made one complete turn. If, then, to each end of the loop there were separately attached a metal collar on the shaft, and on each collar there pressed a spring, wires connected to these springs would convey an *alternating current* to the circuit. If, however, it is desired to adapt the apparatus to furnish a continuous current, a special adjunct must be added.

To commute these alternately-directed currents into one direction in the external circuit, there must be applied a

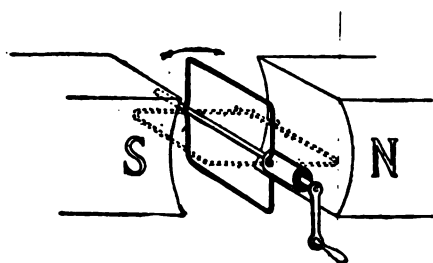


FIG. 18.—IDEAL SIMPLE DYNAMO.

commutator consisting of a metal tube slit into two parts, and mounted on a cylinder of hard wood or other suitable insulating material; each half being connected to one end of the loop, as indicated in Fig. 18. Against this

commutator press a couple of metallic springs or “brushes” (Fig. 19), which lead away the currents to the main circuit. It is obvious that if the brushes are so set that the one part of the split tube slides out of contact, and the other part slides into contact with the brush, at the moment when the loop passes through the positions when the induction reverses itself, the alternate currents induced in the loop will be “commuted” into one direction through the circuit. We should expect, therefore, the brushes to be set so that the commutation shall take place exactly as the loop passes through the vertical position. In practice, however, it is found that a slight forward lead must be given to the brushes, for reasons which will presently appear. In Fig. 20 are shown the brushes B B', displaced so as to touch the

commutator not exactly at the highest and lowest points, but at points displaced in the direction of the line DD , which is called the "diameter of commutation." The argument is in no wise changed if for the single ideal loop we substitute, as proposed by Sturgeon in 1835, the simple rectangular coil represented in Fig. 21, consisting of many



FIG. 19.—TWO-PART
COMMUTATOR.



FIG. 20.
SIMPLE LOOP IN SIMPLE FIELD.

turns of wire, in each of which an simultaneous inductive action is going on, making the total induced electromotive-force proportionately greater. This form, with the addition of an iron core, is indeed, the form given to armatures in 1856 by Siemens, whose shuttle-wound armature is represented in section in Fig. 22. A small magneto-electric machine of the

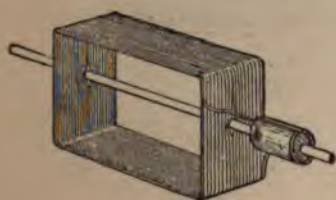


FIG. 21.
SIMPLE RECTANGULAR COIL.



FIG. 22.—SECTION OF OLD SHUTTLE-
WOUND SIEMENS ARMATURE.

old pattern, having the shuttle-wound armature, is shown in Fig. 23. Though this form has now for many years been abandoned, save for small motors and similar work, it gave a great impetus to the machines of its day; but for all large work it has been entirely superseded by the ring armatures and drum armatures presently to be described.

We have seen that the dynamo in its simplest form consists of two main portions: (1) an *armature*, which in revolving induces electromotive forces in the copper conductor wound upon it; (2) a *field-magnet*, that is to say a magnet whose function is to provide a field of magnetic lines, to be cut by the armature conductors as they revolve. In all dynamos, whether for continuous currents or for alternate currents, these two parts can be recognized. In almost all continuous-current machines the field-magnet stands still, and consists of

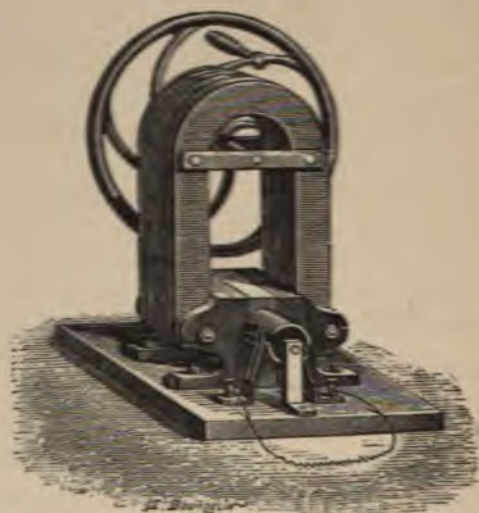


FIG. 23.—OLD SIEMENS MACHINE, WITH SHUTTLE-WOUND ARMATURE AND PERMANENT MAGNETS.

a comparatively simple and massive electromagnet; whilst the armature, which is a more complex structure, is the portion which rotates. In alternate-current machines the field-magnet is usually multipolar, and in the majority of cases is stationary, whilst the armature rotates; nevertheless there are many alternators of recent pattern in which the armature stands still and the field-magnet rotates. The criterion as to which portion is properly called "field magnet," and which "armature," is not the question of rota-

tion or otherwise. The name of field-magnet is properly given to that part which, whether stationary or revolving, maintains its magnetism steady during the revolution; and the name armature is properly given to that part which, whether revolving or fixed, has its magnetism changed in a regularly repeated fashion when the machine is in motion. In a generator the armature is that part which is connected in circuit with the distributing mains and gives current to them. In a motor the armature is that part which receives the currents from the mains. In the case of continuous-current machines there is another feature of first importance, namely, the apparatus for collecting the currents from the revolving armature. This apparatus consists of two essential parts: the *commutator* (or *collector*) attached to the armature and revolving with it, and the *brushes*. The latter, which are conducting contact pieces held pressed against the surface of the rotating commutator, are provided with special *brush-holders* mounted upon an adjustable frame or *rocker*.

In the case of alternate-current machines there is no need of a commutator; but, in general, these machines have to be provided with some device for making a sliding connection. For in those forms in which the armature rotates, its coils must be brought into continuous metallic relation with the conductors of the main circuit; and in those forms in which the armature is stationary and no such arrangement is needed at that part, there must still be sliding contacts to maintain the coils of the revolving field-magnet part in continuous metallic connection with the auxiliary exciting circuit. In either case the appropriate device consists of a pair of *slip-rings*, against each of which a *brush* presses.

In addition to the electrical and magnetic features enumerated above, there are certain purely mechanical features which need to be considered. The revolving part must be mounted on an appropriate *spindle* or *shaft*, the design of which is a matter of mechanical engineering. To transmit the power from the spindle to the revolving conductors of the armature there are required *driving attachments* properly secured to the spindle. The spindle itself must be supported

in suitable *bearings*, and be provided with *lubricators* to secure *cool running*. To receive the power from the engine a *pulley* must be provided, unless the dynamo is to be driven direct by a *coupling* from an engine mounted on the same bed-plate. Lastly, the whole dynamo must be erected upon an appropriate *bed-plate*, which in some cases is placed upon *rails*, so that it may be shifted from time to time by the aid of tightening screws, as the belt grows slack.

In the considerations which follow, attentions will be concentrated upon dynamos for generating continuous currents, the various organs of which will be duly considered. The design of alternate-current machines will be discussed in a later chapter.

ARMATURES.

Returning to the ideal simple loop, we may exhibit it in its relation to the 2-part commutator somewhat more clearly by referring to Fig. 24. The same split-tube or 2-part commutator will suffice if a loop of two or more turns be substituted, as shown in Fig. 25, for the single turn.

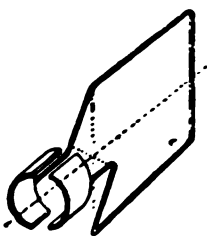


FIG. 24.—SIMPLE LOOP
ARMATURE.

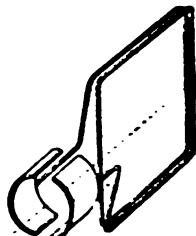


FIG. 25.—LOOP ARMA-
TURE OF TWO
TURNS.

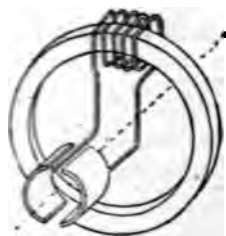


FIG. 26.—SIMPLE RING
ARMATURE WITH
ONE COIL.

But we may substitute also for the one loop a small coil consisting of several turns wound upon an iron ring. This coil (Fig. 26), which may be considered as one section of a Pacinotti or Gramme ring, will be penetrated by magnetic lines as the loop was. In the position drawn, it occupies the highest point of its path, and the flux of magnetic lines

through it will be a maximum. As it turns, the number of lines that penetrate it will diminish, and become zero when it is at 90° from its original position. But a little consideration of its action will suffice to show that if another coil be placed at the opposite side of the ring it will be performing an exactly similar inductive action at the same moment, and may therefore be connected to the same commutator. If these two coils are united in parallel, as shown in Fig. 27, the joint electromotive force will be the same as that due to either separately; but the resistance offered to the current by the two jointly is half that of either. It is evident that we may connect two parallel loops in a similar fashion to one simple 2-part collector. If the two loops are of one turn each, we shall have

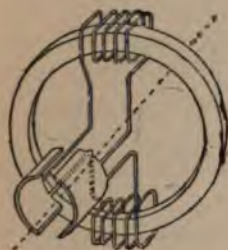


FIG. 27.—SIMPLE RING ARMATURE WITH TWO COILS IN PARALLEL.

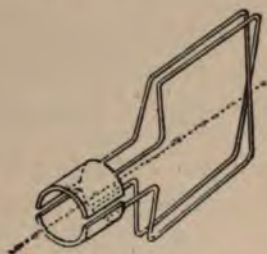


FIG. 28.—SIMPLE LOOP ARMATURE WITH TWO COILS IN PARALLEL.

the arrangement sketched in Fig. 28; but the method of connecting is equally good for loops consisting of many turns each.

Now, with all these arrangements involving the use of a 2-part commutator, whether there be one circuit only or two circuits in parallel in the coils attached thereto, there is the disadvantage that the currents, though commutated into one direction, are not absolutely continuous. In any single coil without a commutator there would be generated, in successive revolutions, currents whose variations may be graphically expressed by a recurring sinusoidal curve, such as Fig. 29. But if by the addition of a simple split-tube commutator the alternate halves of these currents are reversed, so as to rectify

their direction through the rest of the circuit, the resultant currents, though not continuous, will be of one sign only, as shown in Fig. 29, there being two currents generated during each revolution of the coil. The currents are now "rectified,"



FIG. 29.—SIMPLE CURVE OF SINES, REPRESENTING AN ALTERNATING OR UNDULATORY CURRENT.

or "redressed," as our continental neighbors say, but are not strictly continuous. To give *continuity* to the currents, we must advance from the simple 2-part commutator to a form having a larger number of parts, and employ therewith a



FIG. 30.—CURVE OF RECTIFIED OR COMMUTED ALTERNATING CURRENT.

larger number of coils. The coils must also be so arranged that one set comes into action while the other is going out of action. Accordingly, if we fix upon our iron ring two sets of coils at right angles to each other's planes, as in Fig. 31, so that one comes into the position of best action while the other is in the position of least action (one being parallel to the magnetic lines when the other is normal to them), and their actions be superposed, the result will be, as shown in Fig. 32, to give a current which is continuous, but not steady, having four slight undulations per revolution. If any larger number of separate coils are used, and their effects, occurring at regular intervals, be superposed, a similar curve will



FIG. 31.—FOUR-PART
RING ARMATURE
(CLOSED COIL).

be obtained, but with summits proportionately more numerous and less elevated. When the number of coils used is very great, and the overlappings of the curves are still more complete, the row of summits will form practically a straight line,

or the whole current will be practically constant. As arranged in Fig. 31, the four coils are all united together in a *closed* circuit, the end of the first being united to the beginning of the second, and so forth all round, the last section closing in to the first. In order to obtain greater uniformity of effect, the coils on the armature ought to be



FIG. 32.—CURVE OF CONTINUOUS BUT NON-UNIFORM CURRENT.

divided into a very large number of sections (see Chap. IX.), which come in regular succession into the position of maximum effect at regular intervals one after the other. In Fig. 33 a sketch is given of a drum armature wound with two pairs of coils at right angles one to the other, and connected to a 4-part commutator. A little examination of Figs. 31 and 33 will show that each section of the coils is connected to the next in order to it; the whole of the windings constituting, therefore, a single closed coil. Also, the end of one section and the beginning of the next are both connected with a segment of the commutator. In practice, the commutator segments are not mere slices of metal tubing, but are built up of a number of parallel

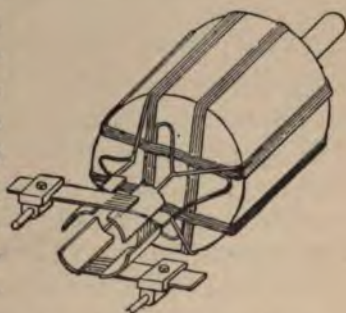


FIG. 33.—FOUR-PART DRUM ARMATURE (CLOSED COIL.)

bars of copper, gun-metal, or phosphor-bronze, such as may be seen in Fig. 36, p. 42, placed round the periphery of a cylinder of some insulating substance. It will also be noticed that, owing to the fact that there is a continuous circuit all round, there are two ways in which the current may flow through the armature from one brush to the other, as in all the ring and drum armatures; of which, indeed, Figs. 31

and 33 may be taken as simplified instances. The same reasoning now applied to 4-part armatures holds good for those having a still larger number of parts, such as is shown in Fig. 34. Of these more will be said in the subsequent chapters. Let it suffice to say here that in closed-coil armatures, whether of the "ring" or the "drum" type, there are usually as many segments to the commutator as there are *sections* or groups of coils in the circuit of the armature. The special case of *open-coil armatures* is considered in Chapter XVIII. In machines of this type the separate coils are not connected up together in series, and a special

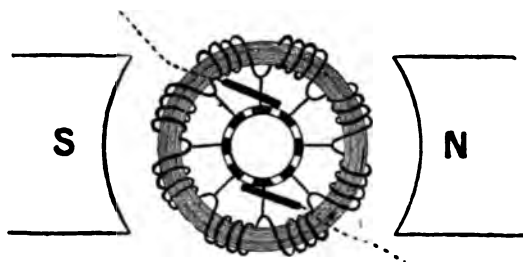


FIG. 34.—SIMPLE RING ARMATURE, SHOWING CONNECTIONS OF CLOSED COIL.

form of commutator is used instead of the usual arrangement of a large number of parallel bars.

So far, the only types of armature considered have been the "drum" type and the "ring" type; but these are not the only possible cases. The object of all such combinations of coils is to obtain the practical continuity and equability of current explained above. To attain this end it is needful that some of the individual coils should be moving through the position of maximum action, whilst others are passing through the neutral point, and are temporarily idle. A symmetrical arrangement of the individual coils or groups of coils around an axis may take one of the four following types:—

(1) *Ring armatures*, in which the coils are grouped upon a ring whose principal axis of symmetry is its axis of rotation also.

(2) *Drum armatures*, in which the coils are wound longitudinally over the surface of a drum or cylinder.

(3) *Pole armatures*, having coils wound on separate poles projecting radially all round the periphery of a disk or central hub.

(4) *Disk armatures*, in which the coils are flattened into a disk.

The ingenuity of inventors has been exercised chiefly in three directions:—The securing of practical continuity, the avoidance of eddy currents in the cores, and the reduction of useless resistance. Most inventors have been content to secure approximate continuity by making the number of sections numerous. Pacinotti's early dynamo had the coils wound between projecting teeth upon an iron ring. Gramme preferred that the coils should be wound round the entire surface of the annular iron core. To prevent wasteful eddy currents in the core, he constructed it of varnished iron wire. For ring cores flat core-disks of sheet iron are now almost universally preferred. For discoidal ring armatures the core is built of hoops. In ring armatures the parts of the copper coils which pass through the interior of the ring are inoperative in cutting magnetic lines, unless there are pole-pieces of the field-magnet projecting internally. Hence, in the ordinary forms of dynamo with exterior magnets, the inner parts of the ring winding act merely as conductors and not as inductors, and offer a certain amount of wasteful resistance. But this resistance in well-designed machines is insignificant compared with that of the external circuit; and the disadvantage is largely imaginary. Inventors have essayed to reduce the amount of copper, by either fitting projecting flanges to the pole-pieces, or by using internal magnets, or else by flattening the ring into a disk form, so as to reduce the interior parts of the ring coils into an insignificant amount. Indeed, the flat-ring armatures may be said to present a distinct type from those in which the ring tends to the cylindrical form. In some large German dynamos of recent type the ring is outside the field-magnets, so that the outer part of the windings are non-inductive or idle; and the

currents are collected direct from the ring by brushes which trail on its periphery. The various modes of winding and connecting up the conductors on an armature are specially considered in Chapter XII. A finished ring armature with its commutator and driving pulley is shown in Fig. 35.

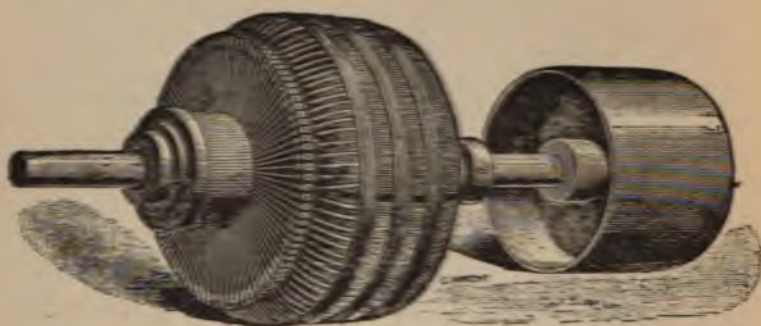


FIG. 35.—RING ARMATURE OF GRAMME DYNAMO (FULLER'S PATTERN).

Drum armatures, as first constructed by Siemens, had iron cores made of wire wound upon an internal non-magnetic nucleus. Weston substituted stamped core-disks of iron with teeth. Edison, iron core-disks without teeth. Special modes

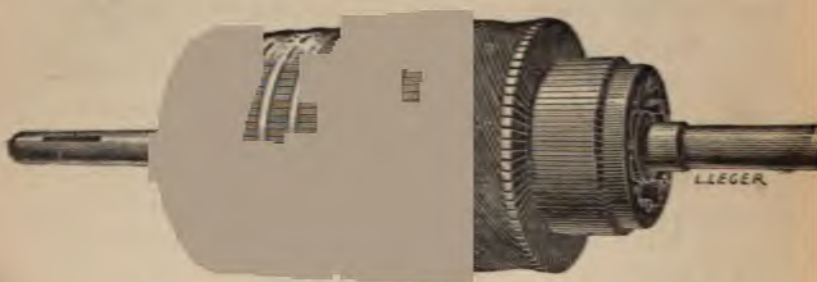


FIG. 36.—DRUM ARMATURE (ALLGEMEINE CO.'S PATTERN).

of winding or joining the copper conductors have been devised by many inventors. A complete drum armature is depicted in Fig. 36, which shows the overlapping of the windings at the end of the drum, the connections to the commutator,

and the external binding wires that keep the coils from flying out.

Pole armatures, having the coils wound upon radially projecting poles, were devised by Allen, Lontin and Weston.

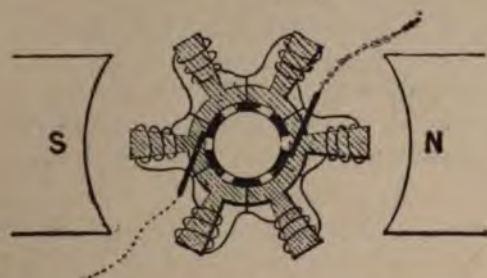


FIG. 37.—SIMPLE POLE ARMATURE SHOWING CONNECTIONS.

The principle of Lontin's machines, in which the coils are connected like the sections of a Pacinotti or Gramme ring, is indicated in Fig. 37. Here the diameter of commutation is parallel to the polar diameter, because the number of magnetic lines in this case is a maximum in the coils that are in the right and left positions. This is not a convenient construction of armature for continuous-current machines; for it does not admit of the winding being divided into a sufficiently numerous set of sections, and the self-induction in each section is too great.

Disk armatures are now differentiated into two kinds: (1) those in which the coils are grouped on a number of small bobbins, side by side, an arrangement suitable for



FIG. 38.—DISK ARMATURE OF DESROZIER'S MACHINE.

alternate-current machines, such as those of Siemens, Ferranti, and Mordey; (2) those in which the windings are made to overlap over a considerable angle of the periphery, as in the disk dynamos of Pacinotti, of Desroziers, and of Fritsche, all of which are adapted to give continuous currents. It is usual in the disk form of armature, to dispense with any iron core; for the armature, being thin, can be inserted in a comparatively narrow gap between the polar surfaces of the field magnet. A disk armature is shown in Fig. 38, belonging to a Desroziers machine.

ARMATURE CORES.

Whenever iron is employed in armatures, it must be slit or laminated, so as to prevent the generation of parasitic eddy-currents. Such iron cores should be structurally divided in planes normal to the circuits round which electromotive-force is induced; or should be divided in planes parallel to the magnetic flux and to the direction of the motion. Thus, drum armature cores should be built of disks of thin sheet iron. Ring armatures, if of the cylindrical or elongated type, should have cores made up of rings stamped out of sheet iron and clamped together side by side; but if of the flat ring type they should be built of concentric hoops. Cores built up of varnished iron wire, or thin disks of sheet iron separated by varnish, asbestos paper, or mica, partially realize the required condition. The magnetic discontinuity of wire cores is, however, to a certain extent disadvantageous; it is better that the iron should be without discontinuity in the direction in which it is to be magnetized. It should, therefore, be laminated into sheets, rather than subdivided into wires. Cores of solid iron are quite inadmissible, as currents are generated in them and heat them. Cores of solid metal other than iron—for example, of gun-metal or of phosphor-bronze—should on no account be used in any armature.

FUNDAMENTAL POINTS IN DESIGN.

As has already been pointed out, the function of the field magnet is to provide a large number of magnetic lines, whilst the function of the armature is to cut the magnetic lines so provided. The iron core inside the armature may be regarded, therefore, as belonging to the magnetic circuit of the field magnet; the true armature consisting of the rotating copper conductors. There is no electrical necessity for the iron core inside the armature to rotate; indeed, in some ways it would act more efficiently if it did not. But purely mechanical considerations require that in both ring armatures and drum armatures the core should rotate with the coils. In all dynamos the electromotive-force is proportional at every instant to the rate at which the magnetic lines are being cut, and this will again be proportional to three quantities: (1) the number of magnetic lines provided by the field magnet; (2) the number of copper conductors connected together upon the armature; (3) the speed at which these conductors are driven. In alternate current dynamos the rate of cutting is continually changing in a regular periodicity; in continuous-current machines the rate of cutting is automatically averaged and made steady by the method of grouping the conductors around the ring or drum in a closed circuit, and connecting to the commutator. It is shown later, on p. 171, that, for continuous-current dynamos of the common two-pole type, the electromotive-force generated in the revolving armature may be calculated as follows:

Let the speed of the armature, or revolutions *per second*, be called n .

Let the number of conductors that are joined in series with one another around the armature be called Z .

Let the number of magnetic lines which pass through the armature core from side to side be called N .

Let the number of volts of electromotive-force generated by the rotating armature be called E .

Then the following formula holds good:—

$$E = a \cdot Z \cdot N = 100,000,000k.$$

Example.—In a Kapp dynamo used at the Technical College, Finsbury, $Z = 1190$; $N = 1,250,000$, at a speed of 700 revs. per min., or 23 revs. per sec., the whole electromotive-force generated is 220 volts.

For alternate-current machines the fundamental formula requires to be completed by the introduction of two additional factors. Such machines are usually multipolar, and if N represents the magnetic flux around any one of the individual magnetic circuits, the total magnetic effect must be increased by multiplying by the number p of pairs of magnetic poles that surround the armature. Further, a constant k must be inserted, the numerical value of which (varying from 1.1 to 2.5 in actual machines) depends on the relative breadths of the coils and pole-pieces employed. The general formula for the volts generated in any alternate-current machine will then be:—

$$E = k \cdot p \cdot a \cdot Z \cdot N \div 100,000,000.$$

Example.—In one of Kapp's alternators, $k = 2.3$; $p = 6$; $Z = 1190$; $N = 1,250,000$, when running at 700 revs. per min.; so that $a = 11.6$, $E = 2700$.

From the above formulae it will be seen that the electromotive-force at which any dynamo is to deliver its current is the product of three factors; and it can be increased by increasing any one of the three, or all of them. In a given machine Z is a constant, and N , the magnetic flux, cannot be increased beyond the capacity of the iron core to carry magnetic lines. But if it is desired to design a new machine, obviously any value might be assigned to any of the three factors, provided the product came to the required amount. It is, therefore, a question of expediency whether in so designing a machine we will increase any one of the factors rather than any other. To increase N means using a larger cross section of iron, and a correspondingly big field-magnet, and therefore involves additional cost of iron. To increase Z means increasing the weight, and therefore the cost of the copper conductors; for the section of these depends on the

current they have to carry, whilst the electromotive-force generated depends on their number, and on the rate at which they cut the magnetic lines. Moreover, experience shows that thus increasing the quantity of copper upon an armature core of given size involves, when once a certain limit is reached, the very serious difficulty that the machine cannot be run without sparking at its brushes. To increase the speed n involves mechanical difficulties about lubrication and liability of the parts to fly out; in fact, mechanical considerations limit the speed. For many years modern practice has gone in the direction of keeping the speed slow, and in keeping down the relative amount of copper, the quantity of iron being relatively large; for not only so is the total cost of the machine less than it would be if the relative amounts of copper and iron were reversed, but the expense and trouble of maintenance is found to be less. Machines with a relatively massive and powerful field-magnet spark less, require less attention to regulation and need fewer renewals of the brushes and commutator than do those which have a comparatively weak field-magnet. Of late there has been some tendency, however, to a movement in the opposite direction, because if, by special designing, without sacrificing the advantages attained in the possession of a relatively powerful field-magnet, the speed and the weight of copper on the armature can be increased, the output of such a machine will be proportionally augmented at a small increase of total weight and total prime cost.

METHODS OF EXCITING THE FIELD MAGNETISM.

The five simple methods of exciting the magnetism that is to be utilized in the magnetic field may be grouped under two heads, according to whether the armature of the machine supplies the machine's own magnetism or whether the magnetism is provided for from some other source.

Magneto-dynamo.—In the oldest machines there was no attempt to make the machine excite its own magnetism, which

was provided for it once for all by the employment of a permanent magnet of steel. Unfortunately, the supposed permanent magnetism of steel magnets slowly decays, and is diminished by every mechanical shock or vibration to which the machine is subjected.

The *magneto-electric machine* or *magneto-dynamo*, a diagrammatic drawing of which is given in Fig. 39, survives, indeed,

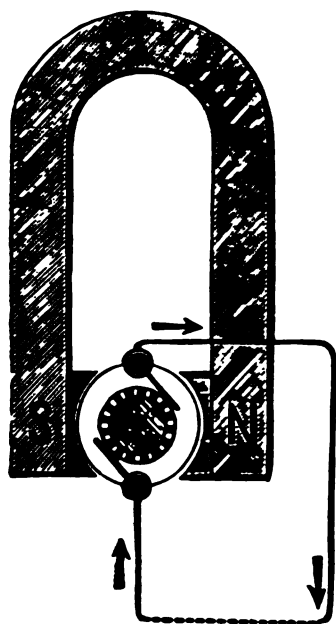


FIG. 39.—THE MAGNETO-DYNAMO.

in numerous small types of machines. It has the serious disadvantage of being both heavier and bulkier than other dynamos of equal capacity, because steel cannot be permanently magnetized to the same high degree as that to which wrought iron or cast iron, or even steel itself, can be temporarily raised.

Separately-excited Dynamo.—

It was an obvious step to substitute for steel magnets, electro-magnets excited by means of currents from some independent source such as a voltaic battery. The *separately-excited dynamo* (Fig. 40) comes therefore second in the order of development.

Though used by Faraday, this method did not come into acceptance until, in 1866, Wilde employed a small auxiliary magneto machine to furnish currents to excite the field magnets of a larger dynamo. The separately-excited dynamo, in common with the magneto machine, possesses the property that, saving for armature reactions, the magnetism in its field, and therefore the total electromotive-force of the machine, is independent of changes of resistance going on in the external circuit.

The dynamos of either of the preceding kinds can be

governed in three different ways: by altering the speed, by putting the brushes forward beyond the neutral point, or by altering the magnetic flux through the armature. For long it has been the fashion to control the electromotive-force of magneto machines by the device of providing a movable piece of iron, which could be placed more or less over the poles of the field-magnet, serving as a magnetic shunt to divert some of the magnetism from the armature. In the case of separately-excited machines there are two other methods of diminishing at will the effective magnetism, namely by weakening the exciting current, for example, by introducing less resistance into the exciting circuit, or, by altering the number of turns of wire through which the existing current circulates around the field-magnet.

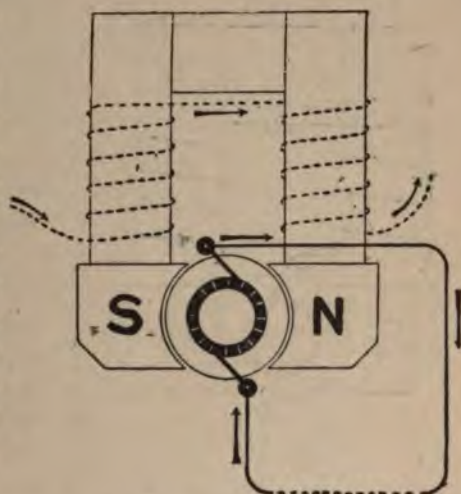


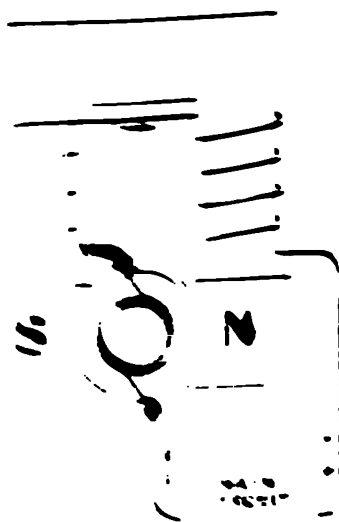
FIG. 40.—THE SEPARATELY-EXCITED DYNAMO.

The elementary methods of making dynamos self-exciting are three in number: (1) the whole current from the armature may be carried through field-magnet coils that are connected in series with the main circuit; (2) a portion of the current from the armature may be diverted from the main circuit and carried through field-magnet coils of somewhat high resistance connected as a shunt; (3) the current required to excite the field-magnet may be procured either from a second armature revolving in the same field, or (if the armature consists of many coils) from some of the coils of the armature that may be separately joined up for that purpose.

Series Dynamo.—The series-wound, or ordinary dynamo

Series-*Electric Machinery.*

series in one circuit. It has the disadvantage of not running until a certain speed has been attained, and the resistance of the circuit is less than a certain limit. It is not able to magnetize its own magnets when the speed is too slow and too little speed. The least objectionable measure of the goodness of the series-wound machines are the difficulties to overcome, a serious disadvantage, and



one that unites this type of machine for employment in electroplating or for charging accumulators. Any increase in the resistance of the series-wound dynamo lessens its power to supply current, because it diminishes the current in the coils of the field magnet, and therefore diminishes the amount of the effect of magnetism. When lamps are in series (as is usual in an arc-light circuit) in the circuit of a series-wound dynamo, the switching on of an additional lamp both adds to the resistance and diminishes the power of the dynamo. On the other hand, when lamps are connected in parallel by a dynamo, if that dynamo is a series-wound one, the switching on of additional lamps increases the resistance of the circuit, but causes the field magnet to be excited by the increased current, so that the more lamps are on the greater becomes the current, and then getting too great a current.

Dynamo. In the shunt-wound machine (Fig. 42) the magnet is wound with many turns of fine wire, to carry a small portion of the whole current generated in

the armature. These coils are connected to the brushes of the machine, and constitute a by-pass circuit or shunt. Shunt machines are less liable to reverse their polarity than series machines. Owing to the somewhat greater cost of the fine wire of the shunt coil, they are slightly dearer in prime cost than series machines of equal power, but the expenditure of electric energy to keep up the magnetism is alike in both cases. It requires the same expenditure of electric energy to magnetize an electromagnet to the same degree, whether the coil consists of many turns of thin wire or of a few turns of thick wire, provided the weight of copper used in the coil be alike in the two cases. When a shunt machine is supplying lamps in parallel, the addition of lamps which brings down the nett resistance of the circuit will increase the current, but not proportionally, for when the resistance of the main circuit is lowered, a little less current goes round the shunt and the magnetism drops a trifle; nevertheless, such a machine may regulate itself tolerably well if the internal resistance of its armature is very small. For a set of lamps in series, the power of a shunt dynamo to supply the needful current increases with the demands of the circuit, since any added resistance sends additional current round the shunt in which the field-magnets are placed, and so makes the magnetic field more intense. The electromotive-force of the shunt machine can be controlled by introducing a variable resistance into the shunt circuit.

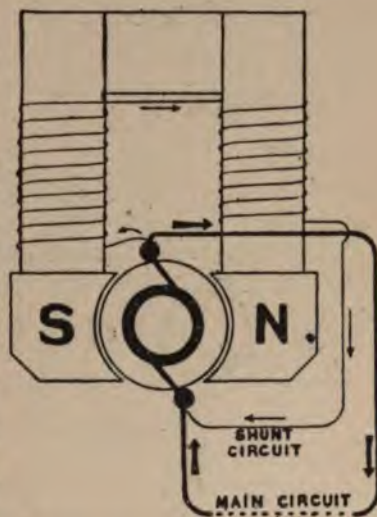


FIG. 42.—THE SHUNT DYNAMO.

A variety of the shunt method involves the use of a *third*

brush, placed against the commutator at some point intermediate between the points of highest and lowest potential. The ends of the exciting coil are connected to the third brush and to one of the ordinary brushes, so that the exciting coil receives a fraction of the volts generated in the armature.

Separate-circuit Self-exciting Dynamo.—There is yet a third species (Fig. 43) of self-exciting machine, in which the field-magnet coils are arranged to form part of a circuit

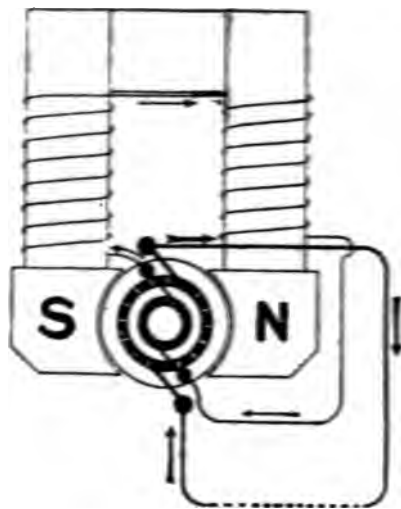


FIG. 43.—SEPARATE-CIRCUIT SELF-EXCITING DYNAMO.

entirely separate from the main circuit, but are supplied with currents from coils rotating in the field. There are two ways of carrying this into effect: (1) a second armature may be made to rotate between the same field-magnets in order to supply the exciting current, each armature having its own commutator; (2) a few of the armature coils may be connected up separately to a special commutator to supply an exciting current.

Holmes, about the year

1868, described a machine having twenty helices in the armature, ten of which supplied alternate currents to the lamps, whilst the remaining ten, or any part of them, could be so connected up through a special commutator as to supply the exciting current to the field magnets. Ruhmkorff attained the same end by winding a second wire upon the Siemens (shuttle-wound) armature, which then was provided with a commutator at each end. The effect of the separate-coil method of excitation is almost identical with that of the shunt method, but it has the advantage that the current thus

taken off for magnetizing may be taken at a low voltage; this being preferable in the case of machines for high voltages. For machines working at 1000 volts and over, the cost of the fine wire for winding a shunt would be prohibitive.

Any of the five systems enumerated may be applied in continuous-current machines. For alternate-current machines, neither series-winding nor shunt-winding is applicable. Each of these five systems of exciting the field magnetism has its own merit for special cases, but none of them is perfect. Not one of these methods¹ will ensure that, with a uniform speed of driving, either the electric pressure at the terminals or the current shall be constant, however the resistances of the circuit are altered.

If all the lamps in the circuit of a dynamo were required to be kept alight, all being turned on and turned off at once—in other words, if the output of the machine were constant—it would matter little how the magnetism of the field-magnet was excited whether in main circuit or in shunt, provided the speed were kept constant. But for systems with a variable number of lamps, none of the simple methods of excitation enumerated above will insure regularity of pressure in the electric supply.

Thanks, however, to the invention of combinations of windings, machines can be made which, when driven at a constant speed, give out their current at a constant pressure. These methods are carefully developed in Chapter XI. They are briefly described here also, so as to complete our summary of the methods of exciting the field-magnets.

COMBINATION METHODS.

There are two distinct cases for which self-regulation is required.

As the function of a dynamo is to feed with sufficiency and regularity a system of lamps, and as those lamps are

¹ An exception exists in the case of a shunt-wound machine if provided with Sayers' special device for enabling the brushes to be set with a backward lead. See Chapter XVI. on dynamo design.

usually in practice ¹ arranged either in parallel or in series, it is clear that in the former case a *constant electric pressure* or *difference of potentials* between the mains, and in the latter a *constant current* is required.

Suppose a dynamo to have an armature of zero internal resistance, without demagnetizing reactions, and to have its field-magnets excited from some independent constant source. At a constant speed it would give a constant potential at its terminals whatever the resistance in the circuit. But if it has internal resistance, the external pressure will be less than the whole electromotive-force, and the discrepancy will be greater according as the internal resistance and the current are greater. Any resistanceless, separately-excited, or shunt dynamo would thus be self-regulating. The drop in the volts due to internal resistance and to armature reaction is nearly proportional to the current taken from the machine, being large when the current is large, and small when the current is small. Hence we may arrange to compensate these effects by an increase of the magnetism that shall also be proportional to the current. This is done by winding on the field magnet a few turns of thick wire to carry the current on its way from the armature to the lamps. It will then give, within certain limits, a constant difference of potentials at its terminals. For distribution *at a constant pressure*, we must have, therefore, dynamos in which there is a combination of *series* coils with some auxiliary independent constant excitation.

It has been hitherto found impracticable to devise any mode of compound winding which will be self-regulating for a constant current. Other modes of regulation are resorted to in the case of machines for series arc lighting for which an unvarying current is needed. These are considered in Chapters XVIII. and XXIX.

¹ Occasionally incandescent lamps are arranged with two, three or more lamps in series, a number of such series being united in parallel across mains that are kept at a constant pressure. Less frequently a few lamps all in parallel with one another are inserted in the circuit of a series of arc lamps through which a current of constant strength is maintained. In any

1, distribution must fall under one or other of the two cases considered.

COMBINATIONS TO GIVE CONSTANT PRESSURE.

The following combinations are all possible solutions of the problem of giving current at a constant pressure:—

(1) *Series and Separate* (Deprez).—A separate and constant excitation is provided from some independent source, so as to bring up the volts on open circuit to the required pressure. The additional excitation needed to raise the magnetism, so as to compensate the lost volts and the armature reaction, is provided by an additional series winding, as indicated in Fig. 44.

(2) *Series and Magneto* (Perry).—The initial excitation may be that of a permanent magnet of steel: but Professor Perry suggested the more general

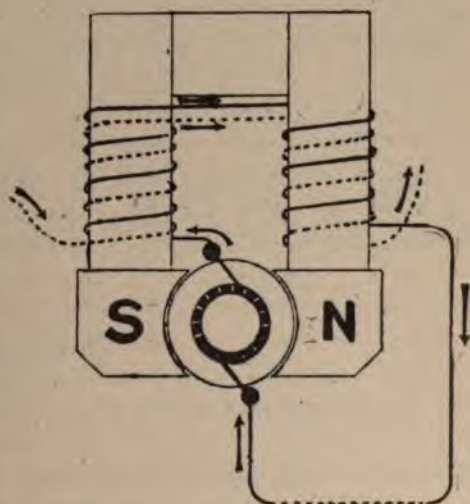


FIG. 44.—COMBINATION OF SERIES AND SEPARATE.

solution of introducing into the circuit of a series dynamo a separate magneto machine also driven at a uniform speed, such that it produces in the circuit a constant electromotive force equal to the pressure which it is desired should exist between the leading and return mains. The series machine only operates to give the additional volts needed for compensating the losses.

The combination of a permanent magnet with electromagnets in one and the same machine, is much older than the

suggestions of either Drexler or Perry, having been described in *Electricity* in 1874.

(3) *Series and Shunt*.—A dynamo having its coils wound as in Fig. 45, so that the field-magnets were excited partly by the main current, partly by a shunt current diverted from

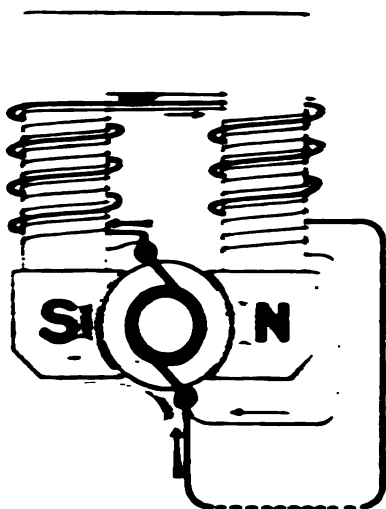


FIG. 45.—SERIES AND SHUNT.

the main circuit, was used by Brush¹ as early as 1875. His machine was very nearly self-regulating, there being less than one volt of variation in the pressure within a wide range of current. The voltage will depend upon the degree to which the magnetism is excited when the shunt is acting alone on open circuit. The arrangement with shunt and series coils is commonly known as a *compound winding*.²

(4) *Series and Long Shunt*.—In 1882 the author proposed to give this name to a combination closely resembling the preceding. If the magnets are excited partly in series, but also partly by coils of fine wire, connected as a shunt not across the brushes but

¹ The shunt part of the circuit, originally called the "teazer," was adopted at first in machines for electroplating, with the view of preventing a reversal of the current by an inversion of the magnetization of the field-magnets, but was retained in some other patterns of machine on account of its usefulness in "steadying" the current.

² The invention of the "series and shunt" winding is claimed for several rivals. Brush undoubtedly first used it commercially, but whether with any knowledge of all its advantages is doubtful. It has also been claimed by Mr. S. A. Varley on the strength of the machine described in his patent specification, No. 4665 of 1876, in which there were two circuits, of different resistance, both wing-coils wound on the field-magnets, and both going to the lamp. He has obtained a decision in the law courts that this strange arrangement anticipated

across the terminals of the external circuit, then the pressure at the terminals should be still more constant.

(5) *Series and Separate-coil*.—This method is not much used. For alternate-current dynamos a modification of it had been used with success, the “series” or main-circuit excitation being, in this case, replaced by an excitation derived from the main current by means of a small transformer, and rectified by a commutator.

that described by Brush. Compound winding was, however, described in 1871 by Sinsteden, in *Pogg. Annalen* (*Supplement Band*, v). 651. It was mentioned as having some advantages by Sir C. W. Siemens in *Philosophical Transactions*, March 1880. It is also claimed for Lauckert (see note by M. Boistel, p. 100 of his translation of first edition of this work); Paget Higgs, (*Electrical Review*, xi. 280, and *Electrician*, Dec. 23, 1882); J. W. Swan, see Bosanquet (*ib.*, Dec. 9, 1882); J. Swinburne (*ib.*, Dec. 23, 1882); S. Schuckert (*ib.*, Oct. 13, 1883). It is claimed in America by Edison; and it has been patented by Messrs. Crompton and Kapp (*ib.*, June 9, 1883). See also Hospitalier (*L'Electricien*, No. 20, 1882). Students should also consult a series of articles in *The Electrician*, vol. x., beginning Dec. 16, 1882, by Mr. Gisbert Kapp. Further, they should see a paper by Dr. Louis Bell in the *Electrical World*, xvi. 383, 1891.

CHAPTER IV.

ACTIONS AND REACTIONS IN THE ARMATURE.

IN this chapter we deal mainly with continuous-current dynamos having armatures of either ring or drum type, and with a simple magnetic field such as is furnished by the two-pole field magnet so common in machines of this class. Many of the considerations apply equally to the case of multipolar machines, to machines with armatures of the disk type, and to alternate-current machines.

For the sake of clearness we will suppose the armature (as viewed from the end to which the commutator is affixed), to be rotating right-handedly ; and we will further suppose that the north pole of the field-magnet is situated on the right hand, as in Figs. 39 to 45, so that the magnetic lines pass through the armature core from right to left. We shall further suppose that the coils on the armature cores are wound right-handedly. Taking this as a standard case it is afterwards very easy to see how a change in any one of these conditions will affect the induction of electromotive-force.

In Fig. 46 these points are illustrated by an end view of a ring armature. The magnetic lines proceeding from the N-pole will cross the adjacent gap-space from right to left, and enter the iron core of the armature ; traversing this (as illustrated in Fig. 60, p. 72), they will then pass across the other gap-space on the left and enter the S-pole of the field magnet. The copper wires or conductors of the armature, as each rises successively in the left-hand gap, will cut these magnetic lines. Each conductor will emerge at the top of the gap, will move over the highest part of the armature from left to right, and in descending the gap-space on the right

will again cut the magnetic lines. If we now apply the rule concerning induction¹ laid down on p. 22, we shall find that the directions of the induced electromotive-forces in these rotating conductors will be as follows:—In all the conductors as they *ascend* through the left-hand gap-space, the direction of the induced electromotive-force is *toward* the observer—whilst in all those that are *descending* the other gap-space on the right the induced electromotive-forces will be directed *from* the observer. If we assume that these electromotive-forces are actually producing currents,² then we may say that the currents flow toward the observer in the conductors which are rising in the left gap-space; and from the observer in those that are descending the right gap-space. If the arma-

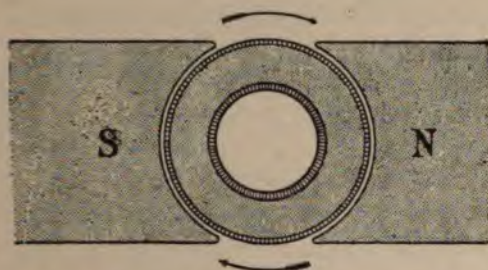


FIG. 46.—END VIEW OF RING ARMATURE BETWEEN TWO-POLE FIELD MAGNET.

ture is wound as a ring, the currents which come in one direction in the gap-space return in the other direction down the inside of the ring. If the armature is wound as a drum, then the currents simply cross at the end of the core through connecting conductors provided for the purpose.

Now consider the way in which the coils on the armature are connected together. Whether wound as ring or drum

¹ See footnote, p. 1.

² In all dynamos, when used as *generators*, the currents being set up by the electromotive-forces are of course in the *same direction* as the electromotive-forces which impel them. But it must be remembered that in the case of machines that are used as *motors* the currents are being sent in by superior electromotive-forces from outside, and that the induced electromotive-forces in the motor's armature are always in an *opposite direction* to that of the current that is flowing.

commutator bars is just leaving contact with a brush, and another one is coming into contact with it, the brush will rest on two adjacent bars and will momentarily short-circuit one section of the coils. While this lasts the two streams that come through the two halves of the winding will flow respectively to the two bars of the commutator, and will thus unite by both flowing into the same brush. It is obvious that if a current is introduced at any point into a closed circuit (such as the winding of a ring) and is taken out at any other point, there must be two paths through the windings. In the case of multipolar machines we shall see there are in many cases more than two paths, the current bifurcating more than once in its way through the armature.

It is evident that if the magnetic lines in the gap-space are more closely crowded together in one part than in another, the electromotive-forces induced in the separate windings as they cut these magnetic lines will be of unequal amount; the greatest electromotive-force being generated in those conductors which are passing through that part of the magnetic field where the lines are crossing the gap most densely. But since the individual conductors are all united together end to end, it will be obvious that the total electromotive-force of either half of the winding, from brush to brush, will be the sum of the electromotive-forces in the separate coils.

INDUCTION IN A UNIFORM HORIZONTAL MAGNETIC FIELD.

In considering the case of an ideal simple dynamo, it was shown that the induction in the rotating loop or coil was zero at the position where it lay in the diameter of commutation, and that the induction increased (as the sine of the angle) to its maximum value at about 90° (see Fig. 18, p. 32). This is of course true for the ideal case of the magnetic lines going straight across horizontally with equal density everywhere. In actual dynamos the distribution of magnetic lines in the gap is different, not always symmetrical, as we shall see.

Returning to the ideal case, Fig. 47, which presents a curve of *sines*, will serve to represent, by the height of the curve the amount of induction going on in an armature at every 10° round the circle. If there are, for example, thirty-six sections in a ring armature, so that the sections are spaced out at 10°

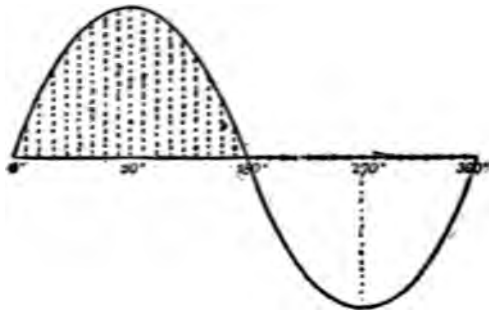


FIG. 47.—CURVE OF INDUCED ELECTROMOTIVE-FORCE.

apart, the least active sections will be those at 0° and 180° , whilst the most active are those at 90° and 270° . But in all the ordinary "closed-coil" armatures, the separate sections are connected together so that any electromotive-force induced in the first section is added on to that induced in the second, and that in the third is added to these two, and so on all the way round to the brush at the other side. The separate electromotive-forces are added together just as are the separate electromotive-forces of a battery of voltaic cells united in series. A ring of battery cells united in series, like Fig. 48, but having one-half the cells set so that the current in them tends to run the other way round the ring, forms a not inapt illustration of the induction in the sections of a ring armature.

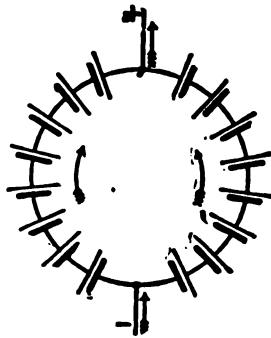


FIG. 48.

Now, knowing how the induction in individual coils or sections rises or falls round the ring, let us inquire what this

will result in when we add up the separate electromotive-forces so as to find the total effect. We shall have to add up the effects of all the sections round, from the negative brush at 0° on one side, to the positive brush at 180° on the other side: and the result will be the same in each half of the ring because of symmetry. Suppose we take the side from 0° by 90° to 180° (on the left in Figs. 20 and 46). If we look at the curve given above (Fig. 47) we shall see that as the heights of the dotted lines represent the amount of induction, the total effect will be got by adding up the lengths of all those from 0° to 180° ; and of course the sum is equal to the sum of the negative lengths between 180°

and 360° . But we may do the thing in another way, which, besides giving us the final total, will show us how the sum grows as each length is successively added on. We should find that the sum grew slowly at first, then rapidly, then slowly again as it neared its highest value. The sum of the effects would grow, in fact, in a fashion represented on a reduced scale in the curve of Fig. 49. This process of adding up a continuously

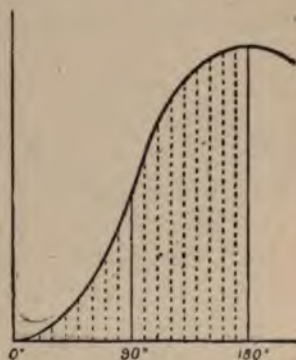


FIG. 49.—INTEGRATED CURVE OF POTENTIALS.

varying set of values is called by mathematicians integrating. Fig. 49 is got by integrating the values of the curve Fig. 47 between the limits of 0° and 180° . Now in the actual dynamo this integration is effected by the nature of things, in consequence of the fact that each section is united to those on either side of it.

It is possible to investigate by experiment¹ either the

¹ For some investigations made by the author, the reader is referred to the author's *Cantor Lectures* delivered in 1883 before the Society of Arts, and which are also described in the earlier editions of this book. The reader should refer to curves of induction obtained by Gauguin (see *Annales de Chimie et de Physique*, 1873), and by Isenbeck (see *Elektrotechnische Zeitschrift*, Aug. 1883). The more recent researches are referred to on p. 65, and in the Chapter on Alternators.

detector galvanometer the position along this wire of the points which have the same potential as that of the pilot-brush on the commutator. Being a zero method it is very accurate; and it dispenses with the voltmeter, which for the preceding method needs to be accurate over a wide range.

Joubert's Method.—Another mode of examining the electromotive-force induced at every successive point in the

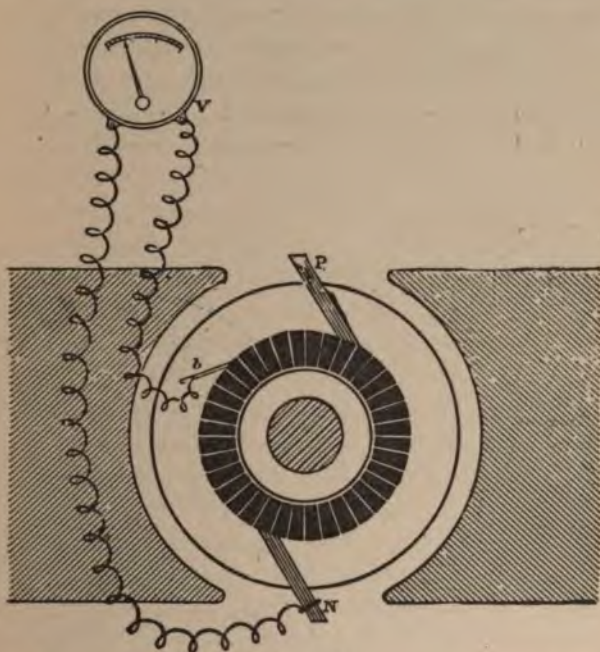


FIG. 51.—MORDEY'S METHOD OF EXPLORING THE POTENTIALS AROUND THE COMMUTATOR.

rotation was devised by M. Joubert,¹ who placed on the shaft of the dynamo a pair of insulated metal collars connected to the ends of the armature winding; each collar having a projecting contact-piece which at each revolution made a moment contact against a spring. The moment at which this occurred

¹ *Annales de l'Ecole Normale*, x. 131, 1881.

depended upon the position of the contact springs, which could be adjusted to different points, and thus enable measurements to be made of the instantaneous values of the electromotive-force at all different positions of the armature. Joubert's method has been used, with some modifications, by Mordey and Raworth,¹ by Ryan,² and by Fleming.³

Mordey's Statical Method—Another method, applicable to machines at rest and without currents in the armature, consists in separately exciting the field-magnets, while the armature coils, or any one of them, are connected to a suitable ballistic galvanometer, and observing the throw caused by the sudden turning off of the current in the exciting circuit. If this is done in a number of successive positions of the arma-

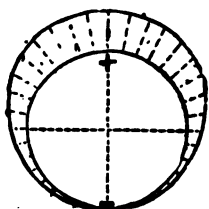


FIG. 52.—DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF GRAMME DYNAMO.

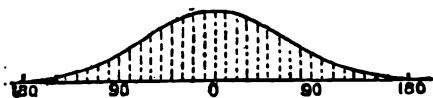


FIG. 53.—HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF GRAMME DYNAMO.

ture, relatively to the field-magnet, a measure is obtained of the density of the magnetic flux, corresponding to each position of the armature, and the result may be plotted out in a curve exhibiting the distribution of magnetism in the field. This distribution is, however, perturbed, as we shall see, when the machine is running by the current in the conductors of the armature.

These indications may with advantage be plotted out round a circle corresponding to the circumference of the commutator. Figs. 52 and 53, which are reproduced from the author's

¹ *Journal Inst. Electrical Engineers*, xviii. 670, 1889.

² *Trans. Amer. Instit. Electrical Engineers*, vii. 3, 1890.

³ *Electrician*, Feb. 22, 1895.

Cantor Lectures of 1883, ^{show} to show how the potential in a good Gramme machine rises gradually from its lowest to its highest value.

It will be seen that, taking the negative brush as the lowest point of the circle, the potential rises perfectly regularly to a maximum at the positive brush. The same values as are plotted round the circle in Fig. 52 are also plotted out as vertical ordinates upon the level line in Fig. 53, which is an actual record taken from an "A" Gramme.

Such curves, plotted out from measurements of the distribution of potential at the commutator, show not only where to place the brushes to get the best effect, but enable us to judge of the relative "idleness" or inductive activity of coils in different parts of the field, and to gauge the actual density of different parts of the field while the machine is running. The steepness of the slope of the curve at different points is in itself a measure of the relative idleness or activity of coils in the corresponding parts of the field.

The rise of potential is not equal between each pair of bars, otherwise the curve would consist merely of two oblique straight lines, sloping right and left from the points of highest and lowest potential respectively. On the contrary, there is very little difference of potential between the commutator bars corresponding to the coils that are relatively idle. The greatest difference of potential occurs where the curve is steepest, at a position nearly 90° from the brushes, in fact, at that part of the circumference of the commutator which is in connection with the coils that are passing through the position of best action. If the magnetic field in which the armature rotated were uniform and parallel, the curve would be a true "sinusoid," or curve of sines. The number of magnetic lines that pass through a coil would be proportional to the cosine of the angle which the normal of that coil makes with the resultant direction of the magnetic lines in the field, and the rate of cutting the magnetic lines should be proportional to the sine of this angle. Now the cosine is a maximum when the angle = 0° and the sine is a maximum when the angle = 90° ; hence the rate of increase of potential should be

at its greatest when the coil is parallel to the magnetic lines—as is very nearly realized in the diagram of Fig. 53, which, indeed, is very nearly a true “sinusoidal” curve.

But in ordinary dynamos with polar surfaces that embrace the armature closely on both sides (as in Fig. 46, p. 59) the field is—at least when not distorted by armature reactions—distributed nearly radially in the gap spaces; and in the parts lying between the pole tips there are hardly any magnetic lines entering or leaving the armature. Hence in such a case the revolving conductors become active as they plunge into the gap, continue nearly equally active as they pass along the gap, and become almost idle when they emerge to pass between the pole-tips. In

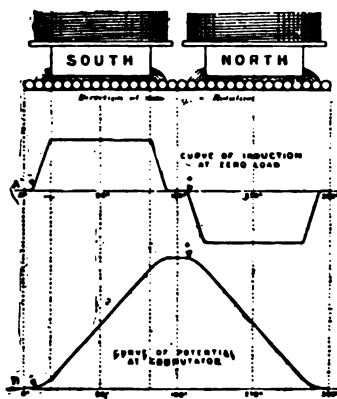


FIG. 54.

such a case the result of exploring the potentials by the first method will be to yield a curve such as A in Fig. 54. The corresponding curve for the total potential measured from the negative point around the commutator by the second method is indicated at B in Fig. 54.

If the brushes are badly set, or if the pole-pieces are not judiciously shaped, the rise

of potential will be irregular, and there will be a maxima and minima of potential at other points. An actual diagram, taken from a dynamo in which these arrangements were faulty, is shown in Fig. 55, and again is plotted horizontally in Fig. 56; from which it will be seen, not only that the rise of potential was irregular, but that one part of the commutator was more positive than the positive brush, and another part more negative than the negative. The brushes, therefore, were not getting their proper difference of potential; and in part of the coils the currents were actually being forced against an opposing electromotive-force.

As we shall see, the current in the armature reacts on the magnetic field, and distorts the distribution of magnetic lines in the gap-space.

These methods of exploring the distribution of potential round the commutator have proved very useful in practice, and elucidated various puzzling and anomalous results found by experimenters who have not known how to explain them.

Curves similar to those given can be obtained from the commutators of any continuous-current dynamo having a closed-coil armature. The open-coil machines used in arc lighting give widely different curves owing to the peculiar



FIG. 55.—DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF A BADLY ARRANGED DYNAMO.

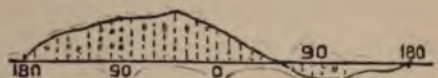


FIG. 56.—HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF FAULTY DYNAMO.

arrangements of their commutators. It should also be remembered that the presence of brushes drawing a current will alter the distribution of potential; and the manner and amount of such alteration will depend on the position of the brushes, as well as on the amount of current drawn and the design of the machine.

Curves showing the actual distortions due to the armature reaction, have been given by von Gaisberg¹ for a Schuckert dynamo, by Kohlrausch² for a Lahmeyer dynamo, and by M. E. Thomson³ for a Thomson-Houston dynamo; also by Ryan (see above).

¹ *Elektrotechnische Zeitschrift*, vii. 67, Feb. 1886.

² *Centralblatt für Elektrotechnik*, ix. 419, 1887.

³ *Electrical World*, xvii. 392, 1891.

REACTIONS DUE TO THE CURRENTS IN THE ARMATURE.

When a dynamo is yielding a current, a set of entirely new phenomena arises in consequence of the magnetic and electric reactions set up between the armature and the field-magnets, and between the separate sections of the armature coils. The current circulating in the armature windings produces magnetizing effects which interfere with those of the exciting currents of the field-magnet. In addition to this there may also be eddy currents in the masses of metal which will perturb the magnetic field. The reactions of the running armature manifest themselves in several ways, the more important of which are (a) a tendency to cross-magnetize the armature; (b) a tendency to spark at the brushes; (c) hence the necessity of shifting the brushes through a certain angle to such a point that sparking disappears; (d) a consequent tendency for the armature current to demagnetize; (e) variations of sparking, and consequently of the neutral points, when the amount of current drawn from the machine is altered; (f) heating of armature cores and coils; (g) heating of the pole-pieces of the field-magnets; (h) a consequent discrepancy between the quantity of mechanical horse-power imparted to the shaft and the electric horse-power furnished in the electric circuit. The nature of these reactions demands careful attention.

Cross-magnetizing Effect of Armature Current.—We have seen (pp. 40, 62, and Fig. 48) that any closed-coil armature

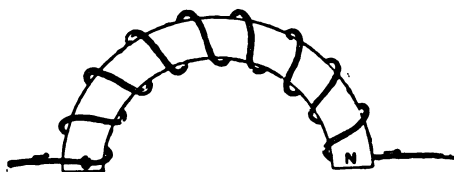


FIG. 57.—POLES ON HALF RING.

may be regarded as acting like a double voltaic battery, the two sets of coils acting like two rows of cells united in parallel.

We have now to show that a ring armature may be regarded also as a double magnet. Suppose a ring of iron to be surrounded, as in Fig. 57, by a coil

carrying a current, it will become, as every one knows, a magnet having a N-pole at one end, and a S-pole at the other. If a complete ring be similarly over-wound, but with an endless winding, and if then electric currents from a battery or other source are introduced into this coil at one point, flowing round the two halves of the ring to a point at the other side, and then leave the coil by an appropriate conductor, each half of the ring will be magnetized. There will be, if the currents circulate as represented by the arrows in Fig. 58, a double (or "consequent") S-pole at the



FIG. 58.—CIRCULATION OF CURRENT
AROUND RING ARMATURE.



FIG. 59.—MAGNETIZATION DUE
TO ARMATURE CURRENT.

point where the currents enter the winding, and a double N-pole at the place where the currents leave. The currents circulating in a Gramme ring will therefore tend to magnetize the ring in this fashion. Let us see how such a magnetization is distributed inside the iron itself. Fig. 59 shows the general course of the magnetic lines as they permeate through the iron; where they emerge into the air are the effective poles of the ring regarded as a magnet. Fig. 59 should be very carefully compared with Fig. 65. It will be noticed that though the majority of the magnetic lines pass externally into the air at the outer circumference of the ring, a few of them find

their way across the interior of the ring, from its N to its S-pole. This part of the magnetic field would in an actual dynamo be deleterious if the number of magnetic lines were not in reality few. The presence of the external masses of iron at the polar parts of the field-magnet tends to cause these magnetic lines to find their way externally.

It is evident that this cross-magnetizing effect will produce a distortion of the magnetic field in the pole-pieces and in the gap-space. If, however, the brushes could be allowed to remain at the ends of a diameter exactly symmetrically between the pole-tips, the effect of the cross field upon the

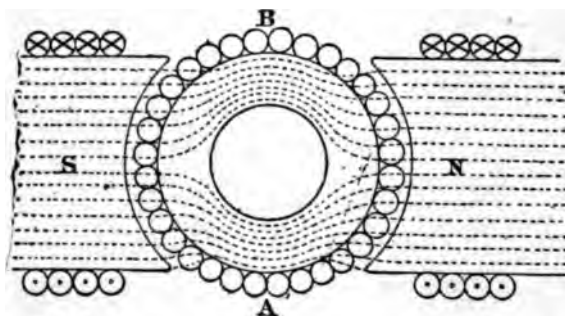


FIG. 60.—MAGNETIC FLUX THROUGH ARMATURE, WHEN NO CURRENT IS FLOWING.

electromotive-force would be inappreciable. But the brushes have to be displaced into an angular position in order to avoid sparking: the diameter of commutation being oblique when the brushes are moved forward to the neutral points. When this is done the armature current produces, as we shall see, not only a cross magnetizing effect, but also a demagnetizing effect; and this weakens the electromotive-force.

Fig. 60 represents¹ the magnetic flux through an armature at rest, when the field-magnets are separately excited. The width of the gap-space is exaggerated, and the conducting wires both on the armature and on the field-magnet are shown in section as if consisting of a single layer of large

¹ Figs. 60, 61, 62 and 63 are taken, with some modification, from Esson's paper in *Journal Inst. Electrical Engineers*, xix. 135. 1890.

round wires. Wires in which a current flows *toward* the observer are distinguished by a central dot. Wires in which a current flows *from* the observer are distinguished by a cross. The reader may think of the dot as representing the point of an arrow advancing towards him ; whilst the cross may represent its retreating tail. Wires carrying no current are left blank. It will be noticed that the magnetic lines are fairly uniformly distributed both in the gap-spaces and in the polar portions of the field-magnet. The armature is drum-wound, the wires being only on the outside ; the magnetizing effect of a current in it will be of the same kind as that traced

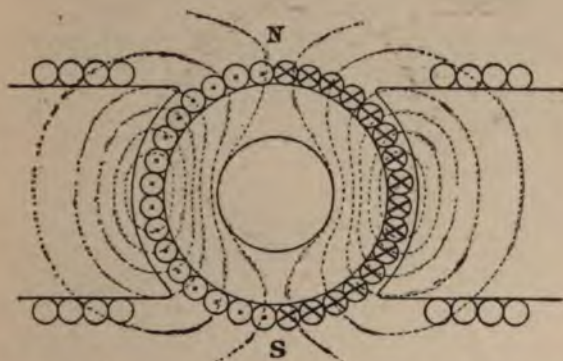


FIG. 61.—CROSS-MAGNETIZING EFFECT OF THE ARMATURE CURRENT.

out above in the case of a ring-wound armature, though less in degree.

Suppose, now, the exciting current in the field-magnet coils to be removed, and a current sent through the armature coils only, so as to imitate the effect of the current generated by the machine when running. If it is to do this, and if the armature connections are in right-handed order, and the machine rotating right-handedly, the currents in both sets of windings will tend to climb toward the top, the upper brush being the positive brush, and the double pole created at B will be a north pole. Suppose the brushes by which the current enters and leaves to be set respectively at the highest and lowest points, as in Fig. 61 ; then the dotted lines may be

taken as representing the flow of magnetic lines due to the currents in the armature. Since the number of such magnetic lines depends upon the goodness of the magnetic path which they have to follow, it is clear that the cross field produced by a given current, flowing in a given set of conductors, will be greater the narrower the gap-space, and the wider the arc spanned by the polar masses of iron¹ on either side. It may also be noted that the cross-flux in either half of the armature must cross the gap-space twice.

But in the actual dynamo, when generating a current, both these magnetizing actions are going on at once. If we super-

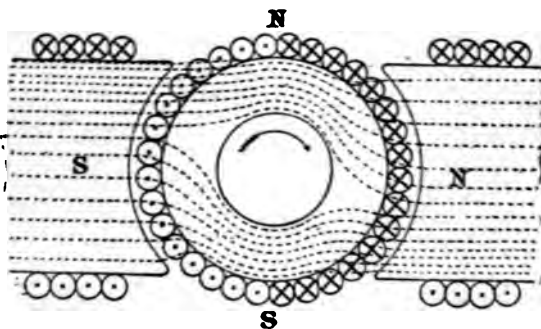


FIG. 62.—JOINT MAGNETIZING EFFECT OF CURRENTS IN FIELD-MAGNET AND ARMATURE (no lead).

pose Fig. 61 on Fig. 60 we shall obtain an approximate picture of the state of things, as Fig. 62. We suppose that the brushes were set to touch at two points on the vertical diameter. The field-magnets tend to magnetize the ring so that its extreme left point is a N-pole, and the currents tend to magnetize it so that its highest point, where the brush is, is a N-pole. The consequence of this will be a resultant magnetization in an oblique direction. The magnetism is thus distorted in the direction of the rotation (in motors it is distorted the other way) as if the rotation of the armature had actually dragged the magnetism round a little. The position of maximum potential will also be shifted a little in

¹ See *Journal Inst. Electrical Engineers*, xx. 290, 1891.

the direction of the rotation. Now for reasons to be shortly discussed, the brushes must be set, not on the diameter that lies symmetrically between the pole-tips, but at an angle a little ahead of this in the direction of the rotation. Hence the cross field will also lie obliquely, tending to further distortion.

Draw a line OF (Fig. 63) to represent the ampere turns due to the field-magnet excitation, and the line OB to represent, relatively in magnitude and direction, the ampere turns due to the armature current; then the diagonal OR will represent the direction and magnitude of the resultant magnetizing tendency.

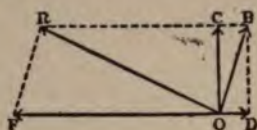


FIG. 63.

An exaggerated diagram of the distortions which result is given in Fig. 64, which relates to a ring-wound dynamo. A

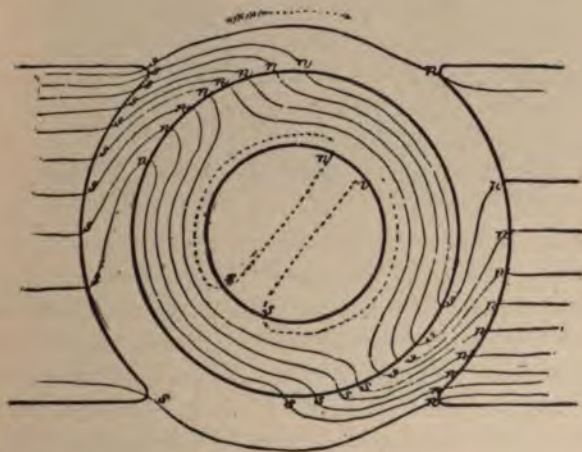


FIG. 64.—MAGNETIC REACTIONS BETWEEN FIELD-MAGNETS AND ARMATURE IN GENERATOR.

reference to Figs. 60 and 62 will also show that the magnetism of the armature reacts on the magnetism of the pole-pieces. The magnetic lines in the iron of the left pole-piece are crowded up towards the top corner, and in the right pole-

piece are crowded towards the bottom, as if the polarity had been attracted upwards on one side and downwards on the other. The density of the field is completely changed from what it was in Fig. 60. The magnetic lines at the upper left side are crowded together. The resultant N-pole of the ring—marked *n, n, n*, where the lines emerge from the ring—attracts the S-pole—marked *s, s, s*, where the lines enter the field-magnet—and the steam-engine which drives the dynamo has to do hard work in dragging the armature round against these attractions. The stronger the current in the armature coils, the stronger will be the poles in the armature, and the stronger will be the attraction of *n, n, n*, toward *s, s, s*; so the steam-engine must work still harder to keep up the speed. It will also be noticed in this figure, which relates to a ring-wound machine, that a *few* of the magnetic lines due to the current in the armature—two of them are shown dotted in the figure—leak across internally and contribute nothing to the external field. The oblique direction of this internal field marks the angle of lead of the brushes. It will be remarked that the innermost layers of iron of the ring are magnetized differently from the outermost, for the “*n*” pole of the outer layer of iron occupies a region lying obliquely on the left, while the “*n*” pole of the inner layers lies to the right of the highest point. All these phenomena—the shifting of the field—its concentration under the “leading” polar horn—its weakening under the “trailing” horn—the weak internal field—the discrepancy between the positions of the induced poles on the inner and the outer sides of the ring, can be observed in an actual dynamo. Fig. 65 shows the pattern produced experimentally in iron filings by placing a magnetized ring between the poles *SN* of a field-magnet, which would tend to induce in it poles *n', s'*, and giving its own poles *n, s* the proper lead. It should be compared with Figs. 62 and 64.

In the case of drum-wound armatures the phenomena, though of the same kind as with ring windings, are a little less easily traced. In consequence of the over-wrapping of the windings on the outside of the armature, the currents in

some of the windings are partially neutralized in their magnetizing effect on the core by those that lie across them, and consequently the polarity due to the current is not so well marked as with ring armatures. Neither can there be any internal field. In fact drum armatures are less liable to induction troubles of all kinds than are ring armatures. But with these exceptions, the same considerations apply to drums as to rings.

A glance at Fig. 61 will show that as the local magnetic fields due to armature currents tend to cross each of the gap-spaces twice, once in the same direction as the principal magnetic field, and once in an opposing direction, there must



FIG. 65.—FIELD OF TWO-POLE DYNAMO.

inevitably result a weakening of the field at that part of the gap where the revolving conductors enter, and a strengthening at that part where they are leaving, exactly as though the revolving copper swept the magnetic lines round while cutting through them. From this distortion there results a similar distortion upon the curve of induction. On exploring with pilot-brush and voltmeter, one obtains curves which differ from those obtained where there is no current in the armature. Fig. 66, which shows the form of the distorted curves, should be compared with Fig. 54, p. 68.

Neutral Points.—From the earliest time that dynamos have been used, engineers have found that, in order that the

sparkless may be maintained, the brushes must be placed in certain positions, to be found by trial, called the *neutral points*. In a primary two-pole dynamo the two neutral points lie at opposite ends of a diameter, which diameter is therefore called the *neutral line*. The term *diameter of commutation* ought to be reserved to denote the position actually occupied by the brushes, or by the coils that are passing the brushes, whether at the neutral point or not. Experience shows that in almost every case the neutral line is not midway between the pole-tips, but lies obliquely across, being in a generator shifted round a few degrees in the direction of rotation. It was

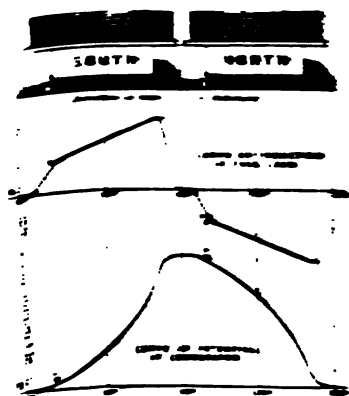


FIG. 8.

early found that in many machines the exact position of the neutral point was different according to the work that the dynamo was doing. If the brushes were set so as not to spark when a certain number of lamps were alight, then, if the load of lamps was altered the machine sparked unless the brushes were adjusted to the corresponding neutral points. Hence arose the practice of mounting the brushes on *rockers* (see Plate III.) by means of which their

line of contact could be altered forward or backward to the neutral point. Great attention has naturally been paid by constructors to the practical problem how to get rid of variations in the angle of lead.

Sparking at Commutator.—Under conditions of faulty design or adjustment, and especially when a large current is flowing through the armature of dynamo or motor, bright sparks of blue or green tint are observed at the commutator just under the tips of the brushes. The greenish tint is due to the volatilization of minute portions of copper. Sparking will spoil or destroy a commutator in a very

short time, and must be imperatively avoided. If a new commutator, or one that has recently had its surface renewed in the lathe, be examined after sparking has taken place, it will be noticed that the edges of many or all of the commutator segments will appear as if burned. But the burnt appearance will always be—no matter whether in generator or motor—at that edge of the segment which was the last to touch the brush; the advancing edge in the direction of the rotation will not show signs of burning. This proves that the spark that produces the damage occurs just as the copper segment, after passing under the brush, parts from contact with it. The *cause* of sparking is not difficult to show. All the conductors in the armature have their currents reversed and re-reversed at every revolution. In bipolar machines the reversal occurs twice in each revolution. In multipolar machines more than twice. In the case illustrated in Fig. 62 the current flows towards the spectator in all the conductors as they rise on the left side, but flows from the spectator in them as they descend on the right. Reversal occurs at the moment when the conductor, or the section of which it forms part, passes the brush or undergoes commutation. The production or non-production of sparks depends on the conditions under which the commutation or reversal of current takes place, and is a consequence of the property of *self-induction*—the property in virtue of which (owing to the current in a conductor setting up a magnetic field of its own in the surrounding space) it is impossible instantaneously to start, stop, or reverse a current.

Consider the standard case of a ring armature constructed in sections, each section consisting of one or two turns of conductor. The currents will be reversed successively in the separate sections, one section at a time, as they come up to the neutral points; or rather two at a time if commutation goes on simultaneously at each of the brushes. Half the current flows up the coils on the left-hand half of the ring, and the other half of the current flows up the coils on the right-hand half. If the positive brush is at or near the top, as in Fig 67, the current flows from left to right through the

sections X and W on the left of the brush, and from right to left through the sections T and U on the right of the brush. Now as the armature turns the bars of the commutator come successively into contact with the brush. In Fig 67 the bars *c* and *d* have already passed the brush; *e* is just leaving it, and *f* is just beginning to pass under it. For a brief moment the brush rests on two adjacent bars *e* and *f*, and thus short-circuits the section V for an instant. The duration will

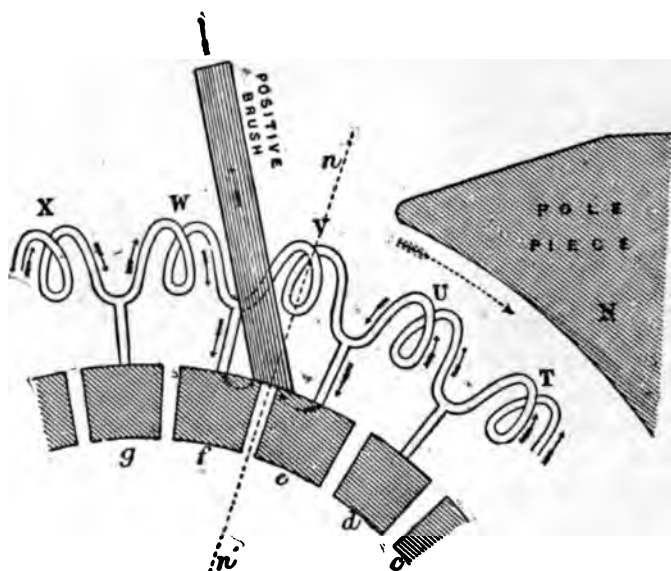


FIG. 67.—THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A GENERATOR.

obviously depend on the speed of rotation, on the breadth of the insulating gap between the commutator bars, and on the breadth of the contact surface of the brush. Now the section V a moment previously belonged to the left-hand half of the ring, and when it has passed the brush, that is to say, when *e* ceases to touch the brush, it will belong to the right-hand half of the ring. It is clear then that in the act of passing the brush the current that was flowing in the section V will be stopped, and then started again in the opposite direction

through its coils. Every section of the armature as it passes the brush will similarly be transferred from one half of the ring to the other, and will have its current reversed. This is in fact the act of commutation. Now suppose it were arranged that the act of commutation should occur exactly at the point when the coils of the section are not cutting any magnetic lines whatsoever: so that while the coil is short-circuited it shall not be the seat of any induced electromotive-force. Then the current in it will die out, and as it emerges from under the brush it will be thrown as a perfectly idle coil upon the right-hand half of the ring, in which a current is flowing toward the brush. Just before the bar e parts company from the brush, the current coming up through T and U is flowing through e to the brush: but as e moves away this current has suddenly to go also round the coils of V. But because of self-induction the current cannot instantly rise to its full strength in the idle coil V, hence before V really gets to work, the current sparks across between e and the brush. We have here supposed V to be a perfectly idle coil: now suppose that it is not idle but is actually still cutting magnetic lines, as would be the case if the brush, instead of being shifted forward to the neutral line $n n'$, had been given a *backward* lead further to the left. Then it is clear that during the moment of short-circuiting there will be an electromotive-force acting in the coil as it passes the brush. Such an electromotive-force, even though small, may produce momentarily a large current, because the short-circuited resistance is so small. Hence the sparkling will be worse than if the coil were absolutely idle. Suppose the section of coil to have a resistance of 0.001 ohm, and to be short-circuited while moving in such a field as to generate 5 volts, the current would rise to 5000 amperes in that coil!

Now suppose that the brush is shifted just so far the other way, in the direction of the rotation,¹ that as the coil passes the

¹ In a case of a motor, which is separately considered in a Chap. XX. the brushes must be shifted in the *opposite* direction to the rotation; i. e. there must be a negative lead.

brush it is beginning to enter the fringe of the magnetic field on the right. In that case it will be beginning to cut the magnetic lines in such a way as to tend to set up a current in the reverse direction through it. The ideal arrangement is attained if the brushes be shifted just so far beyond the point of maximum electromotive-force that while the sections pass under the brush and are short-circuited they should actually have a small reverse electromotive-force induced in them; and this action should last just so long in each successive section as to stop the current that was circulating, start a current in an opposite direction, and let it grow exactly equal in strength to that which is circulating in the other half of the armature, which it is then ready to join. If this set of conditions could be attained there should be *no sparks*. A magnetic field of the proper intensity to cause reversal in the commuted section of the armature can usually be found just outside the tip of the pole-piece, for here the fringe of magnetic lines presents a density which increases very rapidly. Since a more intense field is needed to reverse large currents than is required for small ones, it follows that the angle of lead that must be given to the brushes will be slightly greater for large currents than for small ones. Time must be allowed for reversal, hence the brushes must not be so thin as merely to bridge the width of the insulation. Sparking can indeed sometimes be cured by merely using thicker brushes which prolong the time during which the section is short-circuited.

If the brushes are too thin, or are not rocked sufficiently far forward, there will be free sparking. If they are shifted beyond the neutral points, the sparking is in general less. That is to say there is usually much sparking when the lead is too little; a little sparking when the lead is too great; and no sparking when the lead is right. When the lead is greater than is necessary there is a waste of energy due to the generation in the short-circuited coil of a larger reverse current than is necessary. Moreover, as the lead is increased beyond the neutral point, all the coils that lie in the region

between the neutral point and the diameter of commutation are exerting counter electromotive-forces, and the potential at the brushes falls from its maximum.

If in any dynamo the armature current is very great, and the field-magnet very weak, it may happen that no position can be found for the brushes in which the intensity of the field is sufficient to reverse the current in the section. The greater the magnetic distortion the weaker will be the field just at that very part where a strong field is needed for sparkless reversal. Such a dynamo will spark incurably. It is evident that sparklessness will be promoted (1) by dividing up the armature into many sections, so that the reversals of the currents may be done in detail; (2) by making the field-magnet a relatively powerful one; (3) by so shaping the pole surfaces as to give a suitable fringe of magnetic field of sufficient intensity; (4) by choosing brushes of suitable thickness, and keeping their contact surfaces well trimmed. (See also Chapter XVI. on Dynamo Design.)

Beside the cause of ordinary sparking explained above there are some causes of an exceptional nature. In those dynamos (chiefly those used in arc lighting) that are constructed to work at high potentials approaching or exceeding 1000 volts, there sometimes occurs a phenomenon known as "flashing-over." A long blue spark will on a sudden alteration of the resistance of the circuit be drawn out around the circumference of the commutator from brush to brush. This spark, which is more of the nature of an arc, does little harm in the case of those dynamos which are constructed with commutators of few parts separated by air-gaps, but is very harmful in the case of dynamos having commutators of the ordinary sort, with thin mica insulation between the bars; for these are easily short-circuited by the flash-over.

Another cause of sparking is want of symmetry in the winding of the armature. If one of the sections is short-circuited by any accident, or has become disconnected from its neighbor, sparking will result at that part of the commutator. Jumping of the brushes when the collector is

untrue, or when the brush-holders are defective, is another prolific cause of sparking.

Formerly the fact that a lead must be given to the brushes was ascribed to a sluggishness in the demagnetization of the iron of the armature, but this view is apocryphal. Indeed, the reverse is probably true; and, until further experimental evidence is forthcoming, it will be assumed that the alleged magnetic lag is negligibly small in its effects. For further discussion of this, see some experiments which were described

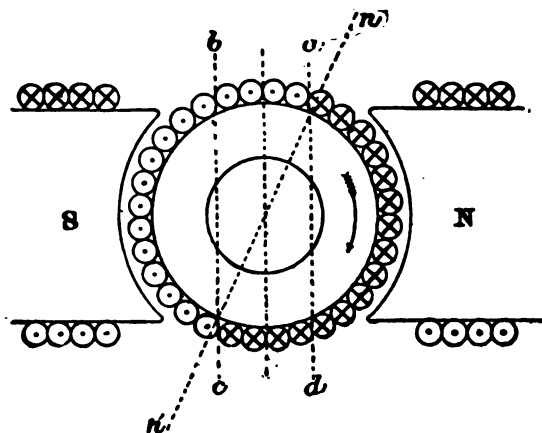


FIG. 68.—DEMAGNETIZING ACTION OF ARMATURE CURRENT OF GENERATOR.

in Appendix V. of the third edition of this work. The generation of eddy currents in any part of the revolving armature will necessarily be accompanied by a demagnetizing action, and will also affect the lead.

Demagnetizing Action of Armature.—If in a dynamo there is a forward lead given to the brushes for the purpose of stopping the sparking, there at once results another reaction, namely, the production of an actual demagnetizing tendency or “back magnetomotive-force.” That the armature current does so act is readily demonstrated by considering Fig. 68. Here the field-magnet and armature are represented as before, but the brushes have been given a

forward or positive lead; the neutral line $n n'$ lying obliquely. The currents are flowing toward the observer in the armature conductors on the left of the neutral line, and from the observer in those on the right of that line. Now let the two lines $a b$ and $c d$ be drawn squarely across the armature through the points of commutation corresponding to the two brushes. These lines intersect the outline of the armature in four points. In the diagram there are thirty-two conductors spaced out around the core disk of the armature; and as this armature is drum-wound, the end connections of the

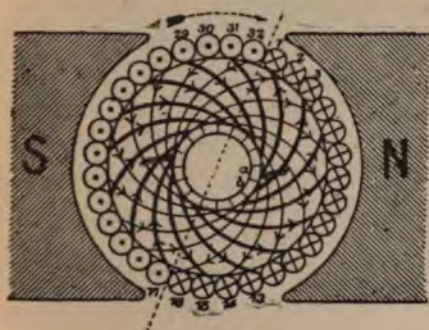


FIG. 69.
ACTUAL CONNECTIONS AT END OF
DRUM-WINDINGS.



FIG. 70.—CONDUCTORS GROUPED
INTO CROSS MAGNETIZING AND
DEMAGNETIZING BELTS.

conductors will probably be somewhat like those shown in Fig. 69, where each conductor is connected across the end by a double-curved connector to the conductor that is next to the one diametrically opposite.¹ Now so far as any magnetizing actions are concerned it does not matter what the end connections are, provided they are compatible with the flow of current indicated above in Fig. 68, with current advancing along the sixteen conductors on the left of $n n'$, and retreating along the sixteen on the right of $n n'$. Hence we may consider them, temporarily, as grouped in any way that will assist us to understand their action. Suppose,

¹ For modes of connecting drum-windings, see Chapter XIII. .

then, that the four conductors from 29 to 32 are joined across the ends¹ to the four from 13 to 16 (Fig. 70); and let the twelve conductors from 1 to 12 be joined across to the twelve from 17 to 28. Our armature windings are now distributed into two belts, one horizontal belt of twelve windings which tends simply to *cross-magnetize*, and one vertical belt of four windings which tends simply to *demagnetize*; for it will be seen that the direction of the circulation around the vertical belt is opposite to the direction of the circulation of current in the magnetizing windings. The breadth of the belt of demagnetizing windings is obviously proportional to the angle of lead, since it subtends double that angle. If the armature in question were carrying 100 amperes then, since there are two paths through the armature circuit (pp. 62 and 71) each conductor must carry 50 amperes. Hence the number of cross-magnetizing ampere-turns is $50 \times 12 = 600$; and the number of demagnetizing ampere-turns is $50 \times 4 = 200$.

Now the cross-magnetizing action which, as we have seen, distorts the field, does of itself slightly diminish the flux of magnetic lines that crosses the armature core from side to side, because in the oblique resultant direction of the magnetization the increased flux tends to produce greater saturation in the pole corners. For other researches on the effect of a cross magnetism in diminishing the magnetism of the core, see papers by Siemens² and Schültze³ in *Wiedemann's Annalen*. Schültze, in the course of twenty-four experiments, found that the cross-magnetization of an iron core always diminished the longitudinal magnetization. More recent experiments on these effects are those of Frölich, Kennelly,⁴ and Stromberg.⁵

In a Manchester dynamo, tested by Prof. Ayrton,⁶ 5846

¹ See Swinburne in *Journal Inst. Elec. Engineers*, xv. 542, 1886.

² Werner Siemens. *Wiedemann's Annalen*, xiv. p. 684, 1882.

³ Schültze. *Wied. Ann.*, xxiv. p. 663, 1885. See also Oberbeck, *Habilitations-Schrift*, 1878.

⁴ *Electrician*, xxv. 111, 1890.

⁵ *Centralblatt für Elektrotechnik*, 1887, p. 283.

⁶ *Journ. Inst. Electrical Engineers*, xix. 175, 1890.

ampere-turns of excitation were needed when no lamps were on, and 10,000 when the machine was furnishing its full output of current; of the additional 4154 ampere-turns, 1754 were needed to compensate for the lost volts (due to internal resistance and lessened permeability) and 2400 to compensate for the demagnetizing effect of the armature current with the increased lead needed to prevent sparking. The greater the lead given to the brushes in a dynamo used as a generator, the greater is the demagnetizing effect of the armature current. In motors the direction of the armature current is opposite to that in the dynamo (that is to say is *against* the electromotive-force), a negative or backward lead has to be given to the brush to avoid sparking—and this backward lead also results in a demagnetizing tendency. If a negative lead (*i. e.* a displacement from the neutral line in the opposite direction to the sense of the rotation) is given to the brushes of a generator, the magnetizing effect of the armature currents will tend to assist the magnetization of the core. Drs. J. and E. Hopkinson¹ have shown that if a backward lead is given, a generator can excite itself by means of the armature currents only; but in such case of negative lead there was a destructive amount of sparking. The demagnetizing effect is of course proportional to the number of effective ampere-turns of the armature circuit that surround the magnetic circuit, and therefore to the actual number of ampere-turns included, as we have seen, in a belt of double the angular breadth of the angle of lead.² According to Kapp a smaller actual number of compensating turns is required in practice. Several expedients have been proposed to compensate the cross-magnetizing tendency of the armature currents, and so obviate the variations of lead. In one due to Mather,³ a small bar electromagnet excited by the armature current is placed perpendicularly between the pole-pieces.

¹ *Phil. Trans.*, 1886, part i. p. 347.

² According to Peukert, who, however, does not specify the angle of lead, the demagnetizing effect of the armature current is proportional to the 1·3 power of the armature current. See *Centralblatt für Elektrotechnik*, ix, 484, 1887.

³ See *La Lumière Électrique*, xix. 404, 1885.

Swinburne¹ has discussed the advantages of various similar arrangements for this purpose. Professor E. Thomson proposes to place a series coil on a movable frame over the armature and tilt it till it brings back the neutral point. These devices, together with the recent proposals of Ryan and of Sayers, are considered in Chapter XVI. on Dynamo Design.

The interference of the armature with the magnetization of field-magnets may also be studied in relation to the "characteristic" curves of dynamo machines (see Chap. X.), which are used to show the rise of the electromotive-force of the machine in relation to the corresponding strength of the current; this rise being proportional to the magnetization through the armature. Now the characteristics of nearly all series-wound dynamos show a decided tendency to turn down after attaining a maximum; and in some machines, for example the older form of Brush arc-light dynamo with cast-iron ring, this reaction is very marked. The electromotive-force diminishes, though the magnetizing force of the field-magnet coils goes on increasing. The effect is due partly to the distortion of the magnetism, but mostly to the demagnetizing effect as the lead of the brushes is increased. It is at least significant that in the older form of Brush machine, where the reduction of electromotive-force is very great, there is also such a mass of iron in the armature, and so variable a lead at the brushes.

The questions of lead of brushes, sparking, and field necessary to reverse the current in a section is further considered in Chapter XVI. in relation to the design of dynamos and the load (or ampere-turns) which an armature can carry.

Dead Turns.—Owing to the various reactions that depend upon the speed, it is found that the electromotive-force of a machine excited by a given current is not rigidly proportional to speed, but falls off somewhat at higher speeds. The machine acts as though some of its revolutions were not

¹ *Journ. Inst. Electrical Engineers*, xix. 105, 1890.

effective. The name *dead-turns* is given to the number of revolutions by which the actual speed at any output exceeds the number that would be needed for strict proportionality.

Spurious Resistance.—There is yet another effect which results from the existence of self-induction in the coils of the armature. In each section the current tends to go on, and in fact does actually go on for a brief time after the brush has been reached. Then the energy of the current in that section is wasted in heating the copper wire during the interval when it is short-circuited; and as it passes on, energy must again be spent in starting a current in it in the inverse direction. All these reactions are of course detrimental to the output of current by the dynamo: especially the loss in short-circuiting. It has been shown by M. Joubert¹ that the loss of energy due to the reversals of the current in the sections of a ring armature is equal to $n L C^2 / 4$ per second, where n is the number of revolutions per second, L the coefficient of self-induction for the entire ring, and C the armature current. Professors Ayrton and Perry very aptly pointed out² that the matter may be conveniently expressed in another way. Since the energy per second conveyed by a current running through a resistance r is equal to $r C^2$, it is evident that the energy lost per-second by self-induction is the same as if there were an additional resistance in the armature of the value $r = n L / 4$. There is, therefore, in a rotating armature, an *apparent* increase of resistance proportional to the speed, and this apparent increase, due to self-induction, cannot be got rid of by subdividing the armature into a larger number of sections. It can be diminished by using more iron in the magnetic circuit, and fewer turns of wire in the armature. The value here assigned depends on the assumption that during the moment of short-circuiting the current in the section simply dies out. If it is stopped and reversed by the introduction of a counter electromotive-force, as it ought to be, the value will be less.

¹ *Comptes Rendus*, June 23, 1880, January 9, 1882, March 5, 1883; and *L'Électricien*, April 1883.

² *Journ. Soc. Teleg. Eng. and Electr.*, xii. No. 49, 1883.

might be induced parallel to the armature conductors ; and in the armature conductors it is desired to cut off all flow of current from one side or edge of the conductor to the other. The planes of lamination must of course be arranged to cut right across the direction in which the parasitic current might otherwise flow. Now since (see p. 23) the direction of the induced electromotive-force, the direction of the motion, and the direction of the magnetic lines are all three at right angles to one another, it suffices in each case to describe the plane of lamination, by stating to which of these three directions it must be normal. It will then contain, or be parallel to, the other two directions.

Direction of	Direction of Lamination Planes.		
	In Armature Cores.	In Armature Conductors.	In Polar Masses.
Motion	parallel	normal	parallel
Magnetic Lines	parallel	parallel	parallel
Induced Electromotive-force..	normal	parallel	normal

It will be noticed that the lamination for the polar masses is the same as for the core ; so that the polar masses are virtually continuations of the core-disks.

The necessity for dividing the cores of drum armatures and of ring armatures (if cylindrical, not discoidal) into core-disks, may be illustrated as follows :—In any conductor rising in the left-hand gap-space there will be generated an electromotive-force tending from back to front. Hence if the core were of solid iron, a current would flow forwards along the outer part of the core on the left, and back along the outer surface on the right. Division of the core into disks will obviously minimize such currents. It will not, however, entirely eliminate them, for as Fig. 71 shows in the sectional view of the core-disks, it is possible for eddy-currents to flow in the substance of these. As a matter of fact it is found that if they are too thick, or are not properly insulated from one another, they heat: and the heating is

mainly at the outer surface, where the eddies are strongest. As a general rule it may be said that core-disks should not exceed 2 millimetres in thickness. The same thickness is suitable for the ribbon cores of discoidal rings. The new laminated armature of the Brush arc-light machine, when used in place of the old solid armature, was found to diminish greatly the number of "dead turns," besides saving much energy previously lost in heating. If there is a stray magnetic field leaking from the flanks of the polar masses into the flat surface of the end-disks of the core, eddy-currents

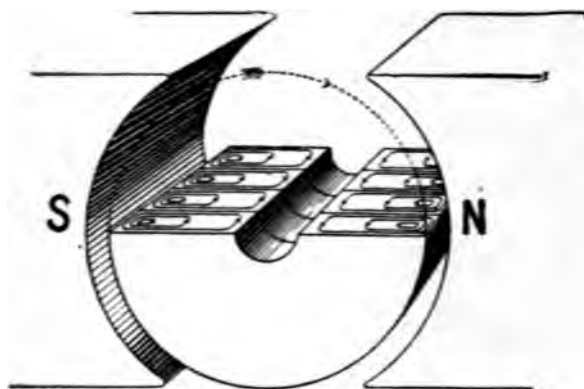


FIG. 71.—EDDY-CURRENTS IN CORE-DISKS.

will also be set up in the latter. This can be obviated by making the length of the armature core rather greater than the length of the polar masses parallel to the axis.

With ring armatures that have an internal field (see p. 71) similar eddies will be set up in the driving spindle and in the metal arms that support the core, wasting power and heating them.

Eddy-currents in Pole-pieces.—If the masses of iron in the armature are so disposed that as it rotates, the distribution of the lines of force in the narrow field between the armature and the pole-piece is being continually altered, then, even though the total amount of magnetism of the field-magnet remains unchanged, eddy-currents will be set up in the pole-

piece and will heat it. This is shown by Figs 72 to 77, which represent the effect of a projecting tooth, such as that of a Pacinotti ring, in changing the distribution of the magnetism of the pole-piece. Figs 75 and 76 (corresponding respectively to Figs. 73 and 74) show the eddy-currents grouped in pairs

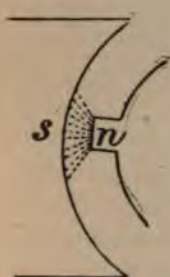


FIG. 72.



FIG. 73



FIG. 74.

ALTERATION OF MAGNETIC FIELD DUE TO MOVEMENT OF MASS OF IRON IN ARMATURE.

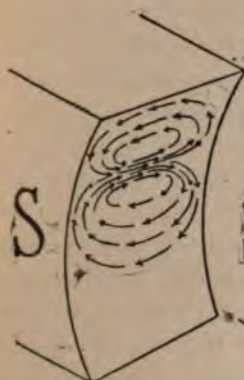


FIG. 75

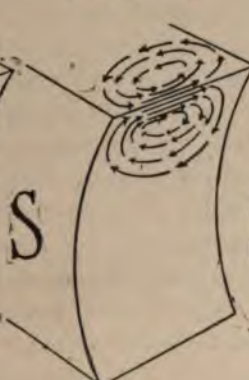


FIG 76.

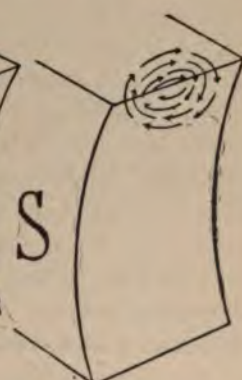


FIG. 77.

EDDY-CURRENTS INDUCED IN POLE-PIECES BY MOVEMENT OF MASSES OF IRON.

of vortices. The strongest current flows between the vortices, and is situated just below the projecting tooth, where the magnetism is most intense; it moves onward following the tooth. Fig. 77 shows what occurs during the final retreat of the tooth from the pole-piece. These eddy-currents penetrate

into the interior of the iron, although to no great depth. Clearly the greatest amount of such eddy-currents will be generated at that part of the pole-piece where the magnetic perturbations are greatest and most sudden. A glance at Figs. 62, 65, 76 and 77 will at once tell us that this should be at the "leading" corner or "horn" of the pole-piece of the generating dynamo. As a matter of fact, when any dynamo which has horned pole-pieces (such as the Gramme) has been running for some time as a generator, this is found to be the case. The "leading" horns *a* and *c* (*i. e.* those which point in the direction of the rotation) are found to be hot, whilst the "trailing" horns are found to be comparatively cool. When the dynamo is used as a motor, the reverse is found to be the case: the "leading" horns are cool, the "trailing" horns are hot. A reference to the magnetic field of the motor, as described in Chap. XX., will explain the latter case. Closely connected with this effect is another, first pointed out to the author by M. Cabanellas. A Gramme magneto-machine with permanent magnets is observed to lose power during its use as a motor; the field-magnets decrease in strength. If, then, it is used as a generator, the field-magnets retain their magnetism. The effect is explicable¹ when the magnetizing effect of the eddy-currents is taken into consideration.

Remedy for Induction Troubles.—The one important way of diminishing these deleterious reactions is happily a very simple one. It is clear that the demagnetizing effect is due to the lead of the brushes, and this again is due to the cross-magnetizing action. This therefore must be compensated or reduced to a minimum by some means. It has been shown that the electromotive-force of the dynamo is proportional to three things, the number n of revolutions per second, the total number N of magnetic lines in the effective field, and the number Z of conductors around the armature. Now, for a given size of armature, the inductive reactions are proportional to Z . If we can decrease Z while increasing either of the other terms, we may thereby decrease the deleterious

¹ See remarks by the author at the International Conference of Electricians at Philadelphia, 1884 (reported in *Electrical Review*, Dec. 13, 1884).

reactions and yet keep the same electromotive-force as before. Now, it is inconvenient for mechanical reasons to increase the speed. The only way then is to increase N , the magnetic flux. This can be done by having relatively big field-magnets. If the field-magnets are large and of wrought iron, and if there is a sufficiently large cross-section of iron in the armature core, then, without increasing the speed, we may get the same electromotive-force while using fewer turns of wire on the armature. The ideal dynamo for constant pressure work has but one turn of wire to each section. It will have practically no lead at the brushes, will not spark, and its internal resistance will be practically *nil*.

It is also important to observe the distortion of the magnetic field and some of the resulting troubles can be partially obviated by so shaping the polar surfaces that they come nearer to the armature at the region at right angles to the diameter of commutation; the pole-pieces being cut away so as to give a wider clearance at the outer edges. It is obviously possible by proper shaping to produce concentration of the magnetic lines at any desired region of the magnetic field. Ryan¹ has made a special study of the relation between the polar shape, the breadth of the gap-space, and the resulting curve of induced electromotive-force. These matters also are discussed in Chapter XVI. under the heading of Dynamo Design.

¹ *Amer. Inst. Electrical Engineers*, Sept. 22, 1891.

CHAPTER V.

MECHANICAL ACTIONS AND REACTIONS IN THE ARMATURE.

Drag on Armature Conductors.—Whenever a conductor carrying an electric current lies in a magnetic field across the magnetic lines, it experiences a mechanical force. This force always tends to drag the conductor sideways out of the field, and acts in a direction at right angles to the magnetic lines and at right angles to the conductor itself. Rules for remembering the relation between the directions of the magnetic lines, the current, and the resulting force, have been given by various writers. The most convenient rule is that of Fleming, in which the three directions are represented respectively by the fore-finger, the middle-finger, and the thumb of the *left* hand.¹ Except in those cases where the conductors are embedded in slots or holes in the iron core-disks, the drag comes on the conductor itself. In a motor it is this drag on the conductors which drives the armature. In a dynamo the drag acts against the driving power of the steam-engine and opposes the rotation. When a mechanical engineer first considers a dynamo he is often puzzled to understand what there is in it that necessitates so much driving power. He sees the armature revolving with ample clearance between the polar faces of the field-magnet. The friction of the bearings

¹ Contrast with p. 23, where, for the current generated in a *dynamo* the *right* hand is used. Remember that in a dynamo the direction of the current agrees with that of the induced electromotive-force, whereas in a motor the current flows against the induced electromotive-force. Further, in the dynamo the mechanical drag acts against the direction of motion, whereas in a motor the drag produces the motion in the same direction as itself. Hence the use of *right* hand for dynamo, *left* hand for motor, to give the relation between magnetism, current and motion.

does not absorb more than a minute fraction of the horse-power delivered by the engine. He sees the brushes pressing against the commutator, but knows that their friction is also a negligible quantity; moreover, he is soon informed that friction has nothing to do with the operation of the machine. Where does the power go to? What is it that requires such a force to be continually exerted to keep up the rotation? The answer is, that there is a continual drag of the invisible magnetic lines on the conductors through which the current is flowing; that the generation of the current depends on the conductors being forced across the field that drags at it. In every form of apparatus generating currents by magneto-electric induction, the currents generated produce a mechanical reaction tending to stop the very motion that generates them.

The drag of a magnetic field upon a conductor that carries a current may be considered from the magnetic point of view.



FIG. 78.—MAGNETIC FIELD OF A STRAIGHT CONDUCTOR CARRYING A CURRENT.



FIG. 79.—MAGNETIC LINES DUE TO CONDUCTOR CARRYING CURRENT PLACED IN MAGNETIC FIELD.

As pointed out on p. 27, above, such a conductor is surrounded by a whirl of magnetic lines. Around a long straight conducting wire not placed in any magnetic field, these magnetic lines form a system of concentric circles (see Fig. 13, p. 27) which are close together near the conductor, and wider apart at a distance away, resembling Fig. 78 in general disposition.

If the current is coming towards the observer, or *up*, in the figure which shows a cross-section of the conductor, the positive direction along the magnetic lines will be counter-clock-wise. If now such a conductor be placed in a uniform



FIG. 80—ACTUAL MAGNETIC FIELD AROUND CONDUCTING WIRE
IN MAGNETIC GAP.

magnetic field—one, for example, between a large north magnetic pole on the right and a south magnetic pole on the left, a compound field will be produced, due to the blending of the magnetic lines of the current with those of the field. In considering this distorted magnetic field it should be remembered that the mechanical actions that result may always be known by supposing the magnetic lines to act as elastic cords tending to shorten themselves. There is in fact a tension along the magnetic lines and a pressure at right angles to them, both proportional at every point to the

square of their density. A mere inspection of the lines of Fig. 79 will accordingly show that there will be a resultant drag upon the conductor in the direction shown by the dotted arrow.

The actual magnetic field produced around a conducting wire in a gap between two poles, as revealed by iron filings, is shown in Fig. 80. We may consider this as approximately representing that which goes on in a dynamo, or in a motor, in each of the gap-spaces between the armature core and the adjacent polar space. Each conductor in the gap will be similarly dragged by a force proportional to the intensity of the magnetic field and to the strength of the current.

Effect of Embedding Armature Conductors.—If the conductors are

embedded in slots or holes in the core-disks (see Figs. 213 to 217) the drag then comes not upon the copper conductors, but upon the iron; the magnetic field between the core-disk and the pole-faces being distorted by the current in the imbedded conductors. In fact the conductor no longer lies in a strong magnetic field; the magnetic lines being carried past

it on either side, very few going through it. Fig. 81 may assist the understanding of this point. It seems paradoxical that though the conductor so imbedded is protected from mechanical drag, and from eddy-currents, owing to its not being in the field, nevertheless in its revolution it still cuts all the magnetic lines precisely as if it were not protected. The effect is as though the magnetic lines flashed across the slots from tooth to tooth, instead of passing across the intermediate slot at the ordinary angular velocity. In addition to the advantages already mentioned as possessed by these forms of construction they have also the very important one of reducing the breadth of the magnetic gap to a mere clearance.



FIG. 81.—MAGNETIC FIELD OF SLOTTED ARMATURE.

Torque and Speed.—Engineers recognize that power, being the rate of doing work, can always be expressed as the product of two factors. In the case of rectilinear motion, the power may be expressed as the product of force and speed. For example, if the force pulling along a belt¹ be equal to the weight of 66 lbs., and the belt-speed be 2000 feet per minute, the amount of power it is delivering is 132,000 foot-pounds per minute, or 4 horse-power.

But the power may be equally well expressed in terms of angular force (*i. e.* torque) and angular speed; and these quantities are more convenient in the case of power transmitted along a rotating shaft.

The useful term *torque*, now generally accepted by engineers, was originally suggested by the late Professor James Thomson. It is the same thing as that which has gone by the names of "turning moment," "moment of couple," "axial couple," "angular force," "axial force," in German by that of "Zugkraft," and in French by those of "effort statique," and "couple mécanique." *Torque* is preferable in many ways to any of the older terms. Just as the Newtonian definition of *force* is that which produces or tends to produce motion (along a line), so *torque* may be defined as that which produces or tends to produce *torsion* (around an axis). It is better to use a term which treats this action as a single definite entity than to use terms like "couple" and "moment," which suggest more complex ideas. The single notion of a twist applied to turn a shaft is better than the more complex notion of applying a linear force (or a pair of forces) with a certain leverage.

For torque we shall use the symbol T . If force f acts with leverage (*i. e.* radius) r , the torque is equal to $f \times r$. If the force is in pounds' weight and radius in feet, the torque will be expressed in pound-feet; *i. e.* in terms of the number of pounds which, acting with a leverage of one foot, would produce an equal tendency to turn. If force is given in dynes and radius in centimetres, the torque will be expressed in dyne-centimetres.

¹ Or more precisely, the difference between the forces in the tight and slack parts.

In order to bring—

dyne-centimetres to gramme-centimetres,	divide by 981
dyne-centimetres to metre-kilogrammes,	divide by 981×10^5
dyne-centimetres to pound-feet,	divide by 13.56×10^6
pound-feet to metre-kilogrammes,	divide by 7.23.

Angular speed is commonly expressed by engineers in terms of the number of revolutions per minute, or, sometimes, of revolutions per second. The scientific mode is to express it in *radians per second*. (The radian is that angle whose arc equals the radius; so that 2π radians equal one revolution or 360° .) The symbol for angular speed is ω , so that if n represents the revolutions per second, $\omega = 2\pi n$.

In order to bring:—

revolutions per minute to revolutions per second,	divide by 60
revolutions per second to radians per second,	multiply by 2π
revolutions per minute to radians per second,	divide by 9.55
radians per second to revolutions per minute	multiply by 9.55

We have then the following relations between linear force f , linear speed v , torque T , angular velocity ω , radius r , revolutions per second n , and power w .

$$w = v.f = \frac{v}{r} . fr = \omega T = 2\pi n T.$$

The power w will be expressed in *ergs per second*, if v is given in centimetres per second and f in dynes; or if T is given in dyne-centimetres. If T is in pound-feet, w will be expressed in foot-pounds per second.

In order to bring :

ergs per second to watts,	divide by 10
ergs per second to kilogramme-metres per second,	divide by 9.81×10^7
ergs per second to foot-pounds per second,	divide by 1.356×10^7
ergs per second to horse-power,	divide by 746×10^7
watts to horse-power,	divide by 746
watts to chevaux-vapeur,	divide by 736
watts to foot-pounds per second,	divide by 1.356
watts to kilowatts,	divide by 1000
kilowatts to horse-power,	multiply by 1.345

Output of Dynamos and Motors.—A good dynamo will convert over 90 per cent. of the mechanical power supplied to it into electric power. Similarly a good motor will convert over 90 per cent. of the electric power supplied to it into mechanical power. Both mechanical power and electric power may be expressed in terms of the same units, either in *horse-power*, or in *watts*, or in *kilowatts*.

Approximate calculations of the horse-power required for a dynamo of any prescribed output are readily made. Multiplying the number of amperes C of current which the dynamo is to yield, by the number of volts e of pressure at which the current is supplied, gives the output in *watts*. Dividing by 746 gives the corresponding electric horse-power, which will be about 90 per cent. of the mechanical horse-power to be supplied to the shaft of the dynamo.

Example: A dynamo is required to furnish 300 amperes (to light 600 glow lamps) at a pressure of 105 volts. Output is 31,500 watts = 42.2 horse-power (electrical). Therefore, allow 46.9, or say 50 (mechanical) horse-power.

In the converse way we may calculate the requisite supply of electric power to a motor.

Example: A motor is required to give an actual output of 5 horse-power. Multiplying by 746, we find it must give out 3730 watts as mechanical power; which will be about 90 per cent. of the electrical power supplied to it. This will therefore need to be about 4144 watts. If the supply is from mains that are at a pressure of 200 volts, the current required will consequently be a little over 21 amperes.

Relation between Torque and Current.—Since the electric power given out by the armature of a dynamo is the product of two factors—volts and amperes—and the mechanical power supplied to it by the rotating shaft is also the product of two factors—speed and torque—it becomes a matter of some interest to ascertain whether there is any direct relation between the factors themselves. Let E stand for the volts generated in the armature, and C_a for the amperes flowing

through it. We may then equate the two separate expressions for the number of watts of power supplied to and furnished by that armature as follows:—

$$\text{watts} = E C_a = 2 \pi n T \times 1.356;$$

where T is given in pound-feet; n in revolutions per second; E the whole volts generated by the armature; and C_a = whole amperes flowing through the armature. But E is proportional to the speed if the magnetism is constant, the fundamental expression for it being (see pp. 46 and 170) for an ordinary two-pole machine,

$$E = n Z N \div 10^8;$$

where Z is the number of conductors around the armature, and N the magnetic flux through its core. Inserting this value for E , and cancelling n from both sides, we get:

$$\frac{Z N C_a}{1.356 \times 10^8} = 2 \pi T;$$

whence

$$\frac{Z N C_a}{8.52 \times 10^8} = T \text{ (in pound-feet).}^1$$

From this it appears that if in a given machine the magnetism is constant, the torque depends in no wise upon the speed, but only upon the current flowing through the armature, and on the magnetism.

These expressions apply equally to dynamos and to motors. They show that if it is desired to build slow-speed machines provision must be made for a very large magnetic flux; for only by making N large can the dynamo at slow speed yield the requisite volts, or the motor exert the needful torque.

A number of curves, called *mechanical characteristics*, giving

¹ If T is desired in metre-kilogrammes, the divisor on the left must be replaced by the value 61.5×10^8 .

the relations between speed and torque in a number of different cases, will be found in Chapter XX.

Drag on Armature Conductors.—We are now in a position to understand the drag on the armature. Setting aside for the moment the case of embedded conductors, we may at once proceed to calculate the amount of such drag. There are three methods of doing this: two being electrical and one a purely mechanical calculation.

METHOD I.—By the last formula the torque is calculated; and from this the total peripheral force is found by dividing by the known radius of the armature. Hence the force per conductor is obtained by dividing the number of active conductors.

Example in the Edison Hopkinson dynamo (Fig. 287), $C_a = 326$; $Z = 80$; $N = 10,850,000$; radius = 0.458 feet; whence $T = 332$ pound-feet, and total peripheral force = 724.7 lbs. This would give about 9 lbs. average force per conductor if all were active; but only about 58 of them are in the magnetic field at one time; hence, the average force per conductor is about 12½ lbs.. If the magnetic field in the gap-spaces is not uniform there comes a stronger drag on those conductors which lie in the densest field.

METHOD II.—The drag on a conductor of length l , in a magnetic field of intensity H , carrying current of C amperes, is

$$f \text{ (dynes)} = C l H \div 10.$$

This formula ¹ is only applicable if H , the density of the field in the gap-space, is known. If l'' and H_{in} are given in inch measures (see p. 126), the formula becomes

$$f \text{ (lbs.)} = C l'' H_{\text{in}} \div 11,303,000.$$

Example, as before: Current in any one conductor will be $\frac{1}{2} C_a = 163$ amperes; $l'' = 20''$, and $H_{\text{in}} =$ about 43,800 lines per square inch, the area of the gap-space being about 250 square inches. Whence drag on each conductor

¹ To give f in kilogramme

METHOD III.—Ascertain actual horse-power on armature ; multiply by 33,000 to reduce to foot-pounds per minute, and divide by the peripheral speed (in feet per minute). [The horse-power may be reckoned from the electrical output as on p. 102]. Then divide by the number of active conductors. Or, in symbols,

$$f(\text{lbs. average drag per conductor}) = \frac{\text{H. P.} \times 33,000}{\text{ft. per min.} \times Z}$$

Example, same as before : Since $i_a = 326$, and $E = 108.5$ volts, $\text{H. P.} = 326 \times 108.5 \div 746 = 47.45$. Also periphery $= 2\pi \times \text{radius} = 2.88$ feet. This, at 750 revs. per minute, gives 2158 feet per minute as peripheral speed. Assuming fifty-eight conductors to be active, we get

$$\text{av. force on each conductor} = \frac{47.45 \times 33,000}{2158 \div 58} = 12.5 \text{ pounds.}$$

A convenient approximate rule may be given as follows :— If we assume, as a sort of rough average for the magnetic field in the gap-space of a dynamo or motor, the value of 40,000 lines to the square inch, or say 6300 lines per square centimetre, then *the drag per inch of conductor will be 0.00354 pound for each ampere of current carried*. In alternate-current dynamos the intensity of the field is seldom more than half as great as this.

Such, then, is the drag that magnetic fields exert upon non-embedded armature conductors ; and, it must be remembered that the drag is not a steady one. When the conductor emerges from the gap-space, though there is still a current in it, the magnetic drag is taken off. Twice, therefore, in each revolution this drag is suddenly removed and suddenly put on again, increasing the racking action. In the case of alternate-current machines, where the relation of phase between the currents and the magnetic fields complicates the matter, the drag is not simply taken off and put on twice in each complete period, but is actually reversed ; the armature conductors being driven with a back drag on them, then

experience a forward drag and tend to drive, then once more are driven, and again tend to drive as the current reverses. In the alternate-current machine acting as a generator the intermediate forward drags are slight and of short duration ; in the machine acting as motor it is the backward drags that are of short duration.

It must further be remembered that the conductors of the rotating armature are also subject to centrifugal force, and must be strongly held in with external binding-wires, or wedged in between the tips of the teeth, if not carried through holes in the core-disks.

Need of Driving Horns.—It is then obvious that under the mechanical conditions now described, if the conductors are not imbedded in the iron cores there is need of a good positive method of conveying the driving power to them from the shaft. In the dynamo, it is they that need to be driven. In the motor, it is they that drive the shaft. The question of construction is complicated by the consideration that whilst the copper conductors must be mechanically connected to the shaft in the most positive way, they must not be metallicly connected, but on the contrary, must be insulated therefrom. Different constructors adopt different modes of accomplishing the end in view. Some makers key on to the shaft a strong hub provided with spokes that project beyond the surface of the core-disks, and, protected by layers of adequate insulation, thus drive the copper conductors. Others secure the core-disks mechanically to the shaft and insert wedges of wood or of hard fibre into nicks in the periphery to serve as driving-horns. In cases where toothed core-disks are used, no other driving-horns are necessary. Compare the practical modes adopted by modern makers described in Chapter XIII.

Stray Power.—In the preceding paragraphs it has been assumed that the mechanical power applied *at the shaft* to drive the armature was equal to the electrical power actually generated in the armature. The power to be applied at the pulley is, however, always greater than this ; for, in the first place, some of the applied power is lost, by friction in the bearings, etc., and never reaches the armature. But of that

which actually reaches the armature, not all is actually converted into electrical power. There are, beside the friction at the bearings and brushes, three sources of loss, viz., (1) air-friction, (2) hysteresis, (3) eddy-currents. The first of these is insignificant, except in those cases where curved spokes are employed with the object of making the armature act as a fan, and even then is small. The second is by no means negligible, but seldom adds more than 1 or 2 per cent. to the driving power. The third is the most important of all, especially in large machines. In all the moving metal masses, unless laminated, there will be eddy-currents set up if they cut magnetic lines. Even in the metal of the shaft, power may be lost from this cause if there is leakage of magnetic lines into it. The mode of investigating the separate sources of loss is described in Chapter XXX. on the Testing of Dynamos and Motors. Whatever these losses, it is evident that they all call upon the supply of power: for the power supplied is necessarily equal to the sum or the power actually converted in the armature into electric power, and the stray power wasted in the ways enumerated.

Efficiency of Dynamos and Motors.—Efficiency is a term used in several senses, which it is well to distinguish.

(1) *Efficiency of Conversion* or *Gross Efficiency*, is the relation between the gross electrical power actually converted in the armature, and the gross mechanical power imparted by belt or coupling to the shaft. If 12 per cent. of the gross mechanical power is lost in friction at the bearings, friction at the brushes, air-friction, hysteresis, and eddy-currents, then the remaining 88 per cent. being actually converted in the armature, we should describe the efficiency of conversion as 88 per cent.

(2) *Electrical Efficiency* or *Economic Coefficient*, is the ratio between the nett electric power or nett output of the dynamo, and the gross electric power, or power actually converted in the armature. Thus, if in a shunt dynamo 3 per cent. of the gross electric power is wasted in heating the resistance of the armature, and another 3 per cent. is wasted in maintaining

the magnetizing current in the shunt winding, the output or nett electric power will be only 94 per cent. of the gross electric power; or the electrical efficiency is 94 per cent. This ratio depends only on the resistances of the machine. In modern machines it may even attain 97 per cent.

(3) *Commercial Efficiency*, or *Nett Efficiency*, is the ratio between the nett electrical output and the gross mechanical power supplied by belt or coupling. It is therefore equal to the product of the efficiency of conversion and the electrical efficiency. In the example given it is 94 per cent. of 88 per cent., or 82.72 per cent.

RELATION OF SIZE TO CAPACITY AND EFFICIENCY.

There has been considerable controversy upon the relation that subsists between the linear dimensions of similar machines and their permissible output and their efficiency; the divergency of views arising mainly as to the assumptions that are suitable at the outset. A few things are certain; for example, the power of getting rid of the heat is only proportional to the surface. It is generally safe to assume that peripheral speeds will not vary much between large machines and small. Amongst those who have discussed the problem are Hopkinson, Frölich, Ayrton, Mascart and Joubert, Kapp, Storch, Rechniewski, and Pescetto. According to Hopkinson¹ the capacity of similar machines is proportional to the *cube* of their linear dimensions; the work wasted in magnetizing the field-magnets is proportional to the linear dimensions, whilst that wasted in heat in the armature conductors is proportional to the square of the linear dimensions. Mascart and Joubert² place the capacity as low as the *square* of the linear dimensions, and draw the conclusion that small machines are preferable to large ones. Prescott³ arrives at similar conclusions. Rechniewski⁴

¹ *Proc. Inst. Civ. Engineers*, April, 1883.

² *Leçons sur l'Électricité*, (1886), ii. 815.

³ *L'Électricien*, xi. 357, 1887.

⁴ *La Lumière Électrique*, xxii. 311.

follows Hopkinson in assigning n^3 as the proportional increase in the capacity of a machine if its linear size is increased n times. Frölich² assigns the value n^4 , and criticises the rule of the fifth power given in 1882 by the author of this work and by Deprez, as involving an increase of n^3 in the current whilst there is an increase of only n^2 in the section of the conducting wires, which is clearly impracticable. Storch³ considers constant-current machines to be in a different category from constant-potential machines. Assuming equal intensity of magnetic-field, equal peripheral velocity, and equal permissible current density, he finds that in all machines the ampere-turns requisite for excitation vary as the linear dimensions. For constant-current machines the capacity is proportional to n^3 that is to say to the weight of the machine, or to the volume of copper on the armature. For constant-potential machines he finds the total length of wire on the armature to be independent of the dimensions of the machines; the number of external armature conductors to vary inversely as the linear dimensions; whilst the capacity of the machines is found to vary as n^4 , though with undue heating, unless the volume of copper on the armature is also increased as n^4 . Storch and Rechniewski agree with Hopkinson that the work lost in field-magnets decreases relatively to that lost in armatures, with an increase in the linear dimensions. On the other hand, increase in the size of the moving masses increases the liability to waste of power by eddy-currents. Kapp⁴ proposes that the speeds of rotation shall be assumed to vary inversely as the linear dimensions, so as to put all machines into equal conditions as regards strains from centrifugal force, and that all the similar machines shall be considered as being worked up to the same safe limit of heating. This involves that the work wasted internally in heat shall be proportional to surface or as $1 : n^2$.

¹ *Die dynamoelektrische Maschine* (1886), p. 168.

² *Centralblatt für Elektrotechnik*, viii. 544, 594, and 743, 1886.

³ *Proc. Inst. Civil Engineers*, lxxiii. 36, 1886.

The resistances, both magnetic and electric, of the field-magnets will be proportional to n^{-1} , and the exciting powers to n^1 . The intensities of field will be proportional to n^1 , and the electromotive-forces to n^1 . The diameters of wires allowed are as n^1 on the magnets and n^1 on the armatures; the resistances of armatures will be proportional to n^{-2} , and the permissible current to n^2 . It follows at once that the capacities of the machine (in watts) will vary as $n^{3\frac{1}{2}}$, whilst the work wasted will vary as n^2 : hence the economic coefficient will increase with the size of the machine. Kapp gives the cost of machines as proportional to $n^{2\frac{1}{2}}$, whence it follows that the cost of a dynamo per lamp varies inversely as its linear dimensions. He gives the following illustrative table:—

Diameter of armature (inches), ...	10	15
Revolutions per minute	1000	670
Number of glow-lamps	150	620
Weight (in tons)	0·5	1·7
Price	100 <i>l.</i>	276 <i>l.</i>
Price per lamp	13 <i>s.</i> 4 <i>d.</i>	8 <i>s.</i> 11 <i>d.</i>
Electrical efficiency (per cent).	80	89

Ayrton² assumes that the speeds of similar machines may be safely put as inversely proportional to the square-roots of the linear dimensions or as to $n^{-\frac{1}{2}}$ instead of n^{-1} . In the larger machines the smaller relative space required for clearance makes admissible the increase of the current in proportion to n^2 . But this increased current would magnetize the iron more highly in proportion, and the electromotive-force would be greater than n^1 , probably nearer $n^{1\frac{1}{2}}$, bringing up the capacity to be proportional to $n^{3\frac{1}{2}}$.

The common opinion of dynamo constructors appears to be that the capacity of dynamos is, for similar machines, a little greater than in proportion to the weight.

Esson² has discussed this question from the point of view of multipolar machines, and finds it a matter of appropriate design whether the efficiency increases or decreases when

¹ *Proc. Inst. Civil Engineers*, 116, 1886.

² *Journ. Inst. Electrical Engineers*, xix. 164, 1890, and xx. 265. 1891.

machines are enlarged in size. He also points out that in increasing all linear dimensions there is greater relative interference of the armature, tending to produce sparking and so to limit the output. He therefore concludes that the output will not be proportional to weight, *i. e.* to n^3 , unless with the larger sizes the surface-speed is somewhat increased.

CHAPTER VI.

MAGNETIC PRINCIPLES ; AND THE MAGNETIC PROPERTIES OF IRON.

As all dynamo-electric machines are based on magnetic principles, it is needful that these should be understood fully. If we once know the relation that subsists between the exciting current and the magnetism that is produced by it, we can apply this knowledge to the design of dynamos : for such knowledge will enable us to calculate beforehand the size of field-magnet and the number and gauge of windings that will be required in a dynamo that is to furnish any given amount of electric energy. It will be necessary first to define the terms used ; then we shall give some account of the facts relating to the magnetic circuit, and of the properties of iron and steel of different kinds. In Chapter VII. follow the method of calculating the reluctance of the magnetic circuit ; some examples and useful rules will be given ; and lastly, the various forms given to field-magnets will be discussed, and calculations respecting them given.

DEFINITIONS AND GENERAL PROPERTIES.¹

Unit Magnetic Pole.—The unit magnetic pole is one of such a strength, that when placed at a distance of 1 centimetre

¹ It is strongly recommended that the reader should make himself familiar with the elementary theory of magnetic phenomena. The author's *Elementary Lessons in Electricity and Magnetism*, published by Messrs. Macmillan and Co., will explain the terms and fundamental facts. The author's work on *The Electromagnet*, published by Messrs. Spon, contains a fuller account of the magnetic properties of iron, and the design and construction of electromagnets. Prof. Ewing's work on *Magnetic Induction in Iron and other Metals* is a standard book of reference.

(in air) from a pole of equal strength, it repels it with a force of 1 dyne.

Intensity of Magnetic Field.—We have seen in Chapter III. that every magnet is surrounded by a certain “field,” within which magnetic force is observable. We may completely specify the properties of the field at any point by measuring the *strength* and the *direction* of that force—that is, by measuring the “*intensity of the field*” and the direction of the lines of force. *The “intensity of the field” at any point is measured by the force with which it acts on a unit magnetic pole placed at that point.* Hence, *unit intensity of field is that intensity of field which acts on a unit pole with a force of one dyne.* There is therefore a field of unit intensity at a point one centimetre distant from the pole of a magnet of unit strength. Suppose a magnet pole, whose strength is m , placed in a field at a point where the intensity is H , then the force will be m times as great as if the pole were of unit strength, and the amount of the force (in dynes) can be calculated by simply multiplying together the strength of the magnetism of the pole and the intensity of the field; or,

$$f = m \times H.$$

Magnetic Lines.—It is possible, in every magnetic field, to draw through any given point, a line in such a direction that it represents the direction of the magnetic force at that point of the field (Fig. 10, p. 24). The iron filing curves formed round magnets show the forms of the otherwise invisible magnetic lines. Even when such lines are not actually drawn, they may be supposed to be drawn; we may even conceive the whole of the space in the magnetic field to be traversed by such lines. Faraday was the first to give a quantitative signification to the conception of magnetic lines. We may use them to specify not only the *direction*, but also the *magnitude* of the magnetic forces by adopting the following convention:—Let there be drawn as many lines per square centimetre of cross section of the field as there are dynes of force (on a unit pole) at the point in question. The symbol H may then be read to mean *either* the number of dynes on

a unit pole, or the number of lines per square centimetre in air; it also may, as we shall presently see, be read to mean the amount of magnetomotive-force exerted, per unit length, along the field.

The convention of magnetic lines enables us to see more clearly what is meant by *magnetic flux*; for looking at Fig. 10, we see the lines issuing from one pole of the magnet like a stream spreading out over the surrounding space and flowing in at the opposite pole. Just as the total number of stream-lines of a liquid remains the same throughout the whole path, so the total number of lines of a magnet passing through a section of the path is the same whatever section we take, provided that our section cuts across the whole of the path. This total number is called the *magnetic flux*, and is symbolized by the letter $\mathbf{N}$. The lines pass through the bar-magnet, Fig. 10, as well as the surrounding space, and thus make a complete *magnetic circuit*. If the ends of the bar were bent round and joined, so as to form a completely continuous ring, then all the lines would circulate within the metal of the magnet, and none in the air surrounding it. We should then speak of the ring as a *closed magnetic circuit*. In the dynamo we try to attain this metallic continuity of the circuit as nearly as possible, consistently with the movability of the rotating parts.

Though the definition of a magnetic line in the air is connected with the force upon a magnetic pole, we are not so much concerned (while considering dynamos), with the forces (exerted on poles by the lines), as with that other phenomenon, the induction of an electromotive-force when a conductor is moved across the lines. Indeed, though we have said that the magnetic lines are continuous throughout the entire circuit, it is really only in so far as their property of generating an electromotive-force is concerned, that they can be regarded as continuous; for the force inside a magnetic material, such as iron, is not represented by the number of magnetic lines per square centimetre, as will be shown when we come to speak of magnetomotive-force. It is only in air, and equally non-magnetic substances that the force is represented by the number of lines per square centimetre. We therefore rather

use the expression "magnetic lines," when speaking of the flux through magnetic material, in contrast to "the lines of force" which emerge into the air. The two are continuous throughout the circuit, and in the air the magnetic lines are the lines of force. Where the lines which represent the direction and amount of any vector quantity, as, for example, magnetic lines or lines of electric flow, are closed on themselves so as to form a circuit, the distribution of the vector quantity is said to be *circuital*. The number of magnetic lines per centimetre of cross section of the magnetic material is aptly called the *flux-density*, and is usually denoted by B . The magnetic force in the material is as before denoted by H , which in fact represents the number of magnetic lines that would exist in the space if the magnetic material were replaced by air while the same causes producing magnetization still existed.

The idea of a magnetic circuit was more or less familiar to Ritchie,¹ Sturgeon,² Dove,³ Dub,⁴ and De la Rive,⁵ the last-named of whom explicitly uses the phrase "a closed magnetic circuit." Joule⁶ found the maximum power of an electromagnet to be proportional to "the least sectional area of the entire magnetic circuit," and he considered the resistance to induction as proportional to the length of the magnetic circuit. Faraday⁷ considered that he had *proved* that each magnetic line constitutes a closed curve; that the path of these closed curves depended on the magnetic conductivity of the masses disposed in proximity; that the magnetic lines were strictly analogous to the lines of electric flow in an electric circuit. He spoke of a magnet surrounded by air being like unto a voltaic battery immersed in water. He even saw the existence of a power, analogous to that of electro-

¹ *Phil. Mag.*, series iii. vol. iii. 122.

² *Ann. of Electr.*, xii. 217.

³ *Pogg. Ann.*, xxix. 462, 1833. See also *Pogg. Ann.*, xliii. 517, 1838.

⁴ Dub, *Elektromagnetismus*, p. 401 (ed. 1816); and *Pogg. Ann.*, xc. 440, 1853.

⁵ De la Rive, *Treatise on Electricity* (Walker's translation), i. 292.

⁶ *Ann. of Electr.*, iv. 59, 1839; v. 195, 1841; and *Scientific Papers*, pp. 8, 34, 35, 36.

⁷ *Experimental Researches*, vol. iii. arts. 3117, 3228, 3230, 3260, 3271, 3276, 3294 and 3361.

motive-force in electric circuits, though the name *magneto-motive-force* is of more recent origin. The same idea is more or less implicitly recognized in the latter half of the magnetic papers in Lord Kelvin's collected volume on Electrostatics and Magnetism. Rowland¹ in 1873 expressly adopted the reasoning and language of Faraday's method in the working out of some new results on magnetic permeability, and pointed out that the flow of magnetic lines of force through a bar could be subjected to exact calculation; the elementary law, he says, "is similar to the law of Ohm." Writing R for the "resistance to lines of force," M for "magnetizing force of helix," and Q for number of "lines of force in a bar at any point," he wrote, for a particular case (a ring-magnet, having therefore a closed magnetic circuit), the equation,

$$Q = \frac{M}{R};$$

an equation for magnetic circuits which every electrician will recognize as being precisely like Ohm's law. He applied the calculations to determine the permeability of certain specimens of iron, steel and nickel. In 1882,² and again in 1883,³ Mr. R. H. M. Bosanquet brought out at greater length a similar argument, employing the extremely apt term "Magneto-motive force," to connote the force tending to drive the total flux of magnetic lines through the "magnetic resistance" (or reluctance) of the circuit. In these papers the calculations were reduced to a system, and deal not only with the specific properties of iron, but with problems arising out of the shape of the iron. Bosanquet showed how to calculate the several reluctances of the separate parts of the circuit, and then add them together to obtain the total reluctance of the magnetic circuit.

¹ *Phil. Mag.*, series iv. vol. xlv. August 1873. "On Magnetic Permeability and the Maximum of Magnetism of Iron, Steel, and Nickel."

² *Proc. Roy. Soc.*, xxxiv. 445, December 1882.

³ *Phil. Mag.*, series v. vol. xv. 205, March 1883. "On Magneto-motive Force." Also *ibid.*, vol. xix. February 1885; and *Proc. Roy. Soc.*, No. 223, 1883; see also *Electrician*, xiv. 291, February 14th, 1885.

In 1886, Mr. Gisbert Kapp,¹ and independently Drs. J. and E. Hopkinson,² introduced magnetic-circuit calculations into the designing of dynamo-electric machines. These methods we shall further consider in the next chapter.

We have seen that N , the magnetic flux from pole to pole of the field-magnet, is an important quantity in the determination of the electromotive-force of a dynamo. Since this total flux depends on (i.) the magneto-motive force, and (ii.) the reluctance of the magnetic circuit, it is necessary to give some consideration to these two quantities.

1. *Magnetomotive-Force or Total Magnetizing Power of Electric Current circulating in a Coil.*—It is found that when a current flows along in a wire that is coiled in several turns around a core (Fig. 82), and is thus made to circulate

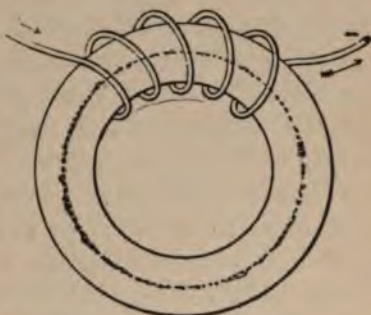


FIG. 82.—MAGNETIZING COIL WOUND AROUND A MAGNETIC CIRCUIT.

around an interlinked magnetic circuit, the magnetizing power is proportional both to the strength of the current so circulating and to the number of turns in the coil. The magnetizing power is independent of the size or material of the wire, and of its shape, and is the same whether the spirals are close together or wide apart. If S stands for the number of *spirals* in the coil, and C be the number of *amperes* of current that are flowing, then C multiplied by S will be the number of *ampere-turns* of circulation of current. It is experimentally proved that twenty amperes circulating around five turns exert precisely

¹ *Journal Soc. Telegraphic Engineers and Electricians*, xv. 524-529, November 11th, 1886. "On the Predetermination of the Characteristics of Dynamos"; a very valuable paper marred by mixed units. Those who wish to study examples of this mode of calculating, will find some examples in a paper communicated by Professor Jamieson in Jan. 1889, to the *Institution of Engineers and Shipbuilders in Scotland*; vide *Electrician*, March 1, 1889.

² *Phil. Trans.*, part i. p. 331, 1886.

the same magnetizing power as one ampere circulating one hundred times, or as one hundred amperes circulating once around the core. In each of these cases the circulation of current is one hundred ampere-turns. To calculate from this the value, in absolute C.G.S. units, of the magnetomotive-force, it is requisite to multiply the ampere-turns by $\frac{1}{10} \pi$, or by 1.257. Or, in symbols,

$$\text{Magnetomotive-force} = 1.257 \times \text{C S.}$$

It is possible to avoid the use of this multiplier by taking the ampere turns themselves as the magnetomotive-force. In that case one applies a coefficient to the calculation of the reluctance of the circuit (see p. 146).

Some writers¹ call the magnetomotive-force the "line-integral of the magnetic forces." The reason is as follows:—In a field of intensity H , a unit magnetic pole experiences a force numerically equal to H ; and if the unit were moved against this force once around a closed path of length l (like the dotted line in Fig. 82), the work done would measure the integral magnetic force. Hence along a length l in a field of intensity H the magnetomotive-force is equal to $H \times l$. Hence it also follows that the intensity of the field along a uniformly wound coil is expressed by the formula:—

$$H = 1.257 \times \text{C S} \div l.$$

In other words is proportional to the ampere-turns per unit of length.

There are some analogies between a magnetic circuit and an electric circuit, which considerably simplify the magnetic principles relating to dynamo construction.²

Just as there are some materials which conduct the electric

¹ See Maxwell's *Electricity and Magnetism*, vol. ii, art. 499; or S. P. Thompson's *Elementary Lessons on Electricity and Magnetism* (edition of 1895), p. 334.

² It should be observed that, though for the purpose of this simplification, it is allowable to draw an analogy between an electric circuit and a magnetic circuit, the true magnetic analogue of an electric circuit (in which energy is being continually transported) would be a circuit in which energy is being transported by the passage of "free magnetism;" but no conductors of magnetism in this sense are as yet known.

current better than others, so there are some materials which conduct the magnetic flux better than others. The reluctance or resistance of a circuit in each case is proportional to the length of the path, to the reluctivity or resistivity of the material, and inversely proportional to the cross section of the path. Just as in a battery the total electromotive-force is made up of the separate electromotive-forces of all the cells joined in series, so the total magnetomotive-force in a magnetic circuit is the sum of the magnetomotive-forces separately produced by each coil of wire. If the magnetic circuit is branched (as in the Manchester dynamo shown in Fig. 101, No. 24), then the coils on the separate branches do not have their forces added together, but are analogous to batteries placed in parallel with each other.

We have a difference of magnetic potential between the ends of core wound with a magnetizing coil just as we have a difference of electric potential at the terminals of a cell. As we go along the magnetic circuit the potential falls by an amount equal to the reluctance of the path multiplied by the total flux. The iron inside a magnetizing coil may be said to be for the purpose of diminishing its "internal" reluctance. We have stout iron frames for our dynamos in order that the magnetic pressure of the coils may be transferred to the armature without appreciable "drop." The fall of magnetic potential in a column of air per centimetre of length is numerically equal to the flux-density. Therefore, to calculate the magnetomotive-force necessary to create a certain flux-density in a certain air-space, we have only to multiply the flux-density by the length of the air-space.

Thus to produce a flux-density of 10,000 lines per square centimetre in an air-gap 1 centimetre in length will require a magnetic pressure of 10,000 *gausses*, a gauss being the magnetomotive-force required to produce unit flux-density in an air-space 1 centimetre in length.¹ One ampere-turn produces a magnetomotive-force of 1.257 *gausses*, so that to produce a flux-density of 10,000 in an air-gap 1 centimetre

¹ It requires 2.54 *gausses* or 2.02 ampere-turns to produce unit flux-density in an air-space 1 inch in length. See note on p. 144.

in length will require $\frac{10,000}{1.257}$ ampere-turns. We might calcu-

late the ampere-turns required on a dynamo field-magnet by multiplying the flux-density by the total length of air-gap and dividing by 1.257, and then add some further turns to make up for the drop in magnetic potential in the iron circuit; but it is more usual to find the total reluctance of the circuit and multiply by the total flux in the manner shown in Chapters VII. and XVI.

2. *Reluctance of Magnetic Circuit.*—We have seen that, other things being equal, the total flux in a circuit is inversely proportional to the reluctivity of the materials of which it is composed; it is directly proportional to the *permeability* which is the reciprocal of *reluctivity*.

The permeability of a material is the numerical coefficient which expresses the ratio between flux-density B , and the magnetizing force¹ H . For instance, if a column of air is subjected to a magnetizing force H , the number of magnetic lines per square centimetre of cross section, in other words the flux-density B , is equal to H ; therefore, the ratio $\frac{B}{H} = 1$ and we say the permeability of the air is 1. If we take a piece of iron and subject it to the same magnetizing force H we find

¹ The following are the various ways of expressing the three definitions :

B—The number of lines per square centimetre in the material.

The flux-density.

The magnetic displacement.

The internal magnetization.

The magnetic induction.

The induction.

The intensity of the induction.

The permeation.

H—The number of lines per square centimetre that there would be in air.

The magnetizing force at a point.

The magnetic force at a point.

The intensity of the magnetic force.

The rate per cm. of fall of magnetic potential.

The magnetomotive-force per unit length.

μ —The magnetic permeability.

The permeability.

The specific conductivity for magnetic lines.

The magnetic multiplying power of the material.

that B is very much greater. For example, a certain specimen of iron, when subjected to a magnetic force capable of creating, in air, 50 magnetic lines to the square centimetre, was found to be permeated by no fewer than 16,062 magnetic lines per square centimetre. Dividing the latter figure by the former gives 321 as the value of the permeability, that is to say, the permeability of the iron at this stage of the magnetization is 321 times that of air. The permeability of such non-magnetic materials as silk, cotton and other insulators, also of brass, copper and all the non-magnetic metals, is taken as one, being practically the same as that of the air.

The permeability of iron, however, varies very greatly with the degree to which it has been magnetized. In all kinds of iron (after passing the initial stage mentioned below) the magnetizability of the material becomes diminished as the actual magnetization is pushed further; there is in fact a tendency to magnetic saturation. In other words, when a piece of iron has been magnetized up to a certain degree, it becomes, from that degree onward, less permeable to further magnetization, and though actual saturation is never reached, there is a practical limit beyond which the magnetization cannot well be pushed. Joule was one of the first to establish this tendency toward magnetic saturation. Modern researches have shown numerically how the permeability diminishes as the magnetization is pushed to higher stages. The practical limit of the flux-density, B , in good wrought iron, is about 20,000 magnetic lines to the square centimetre, or about 125,000 lines to the square inch; and in cast iron the practical saturation limit is nearly 12,000 lines per square centimetre, or about 70,000 lines per square inch.

In designing electromagnets, before calculations can be made as to the size of a piece of iron required for the core of a magnet for any particular purpose, it is necessary to know the magnetic properties of that piece of iron; for it is obvious that if the iron be of inferior magnetic permeability, a larger piece of it will be required in order to produce the same magnetic effect as might be produced with a smaller piece of higher permeability. Or again, the piece having inferior

permeability will require to have more copper wire wound on it; for in order to bring up its magnetization to the required point, it must be subjected to higher magnetizing forces than would be necessary if a piece of higher permeability had been selected.

CURVES OF MAGNETIZATION.

A convenient mode of studying the magnetic facts respecting any particular brand of iron is to plot on a diagram the curve of magnetization—*i. e.* the curve in which the values, plotted horizontally, represent the magnetic force, H , and the values plotted vertically those that correspond to the respective flux-density, B .

Thirty-five samples of various irons of known chemical composition were examined by Hopkinson,¹ the two most important for present purposes being an annealed wrought iron and a gray cast iron, such as are used by Messrs. Mather and Platt in the construction of dynamo machines. Hopkinson embodied his results in curves, from which it is possible to construct, for purposes of reference, numerical tables of sufficient accuracy to serve for future calculations.

The upper curve, Fig. 83, gives the behavior of annealed wrought iron.² The ascending line shows the relation between the intensity of the magnetizing force H and the flux-density B during the process of increasing the magnetizing force from zero to about 220; and the descending line shows the same relation during the process of decreasing the magnetizing force to zero, and then reversing it so as to remove the residual magnetic lines. The lower curves show the behavior of *gray cast iron*.

Every sample of iron will show, on being tested, a similar set of facts which can be plotted down as a curve that is characteristic of the relation in question; but the curves for cast iron and steel always lie lower than those for wrought iron. Moreover, it will usually be noticed that when a fresh piece of iron or steel is subjected to a gradually increasing

¹ *Phil. Trans.*, pt. ii. p. 455, 1895.

² Hopkinson in *Phil Trans.*, pt. ii. 455, 1895.

magnetizing force, the lowest part of the curve presents near its origin a small concavity (see Fig. 83), showing that there is a certain stage where under small magnetizing forces the permeability is greater than at the initial stage. This concavity is more pronounced in the case of hard iron and of steel than in the case of soft iron. But the curves differ in detail even in different specimens of the same sort of iron. In

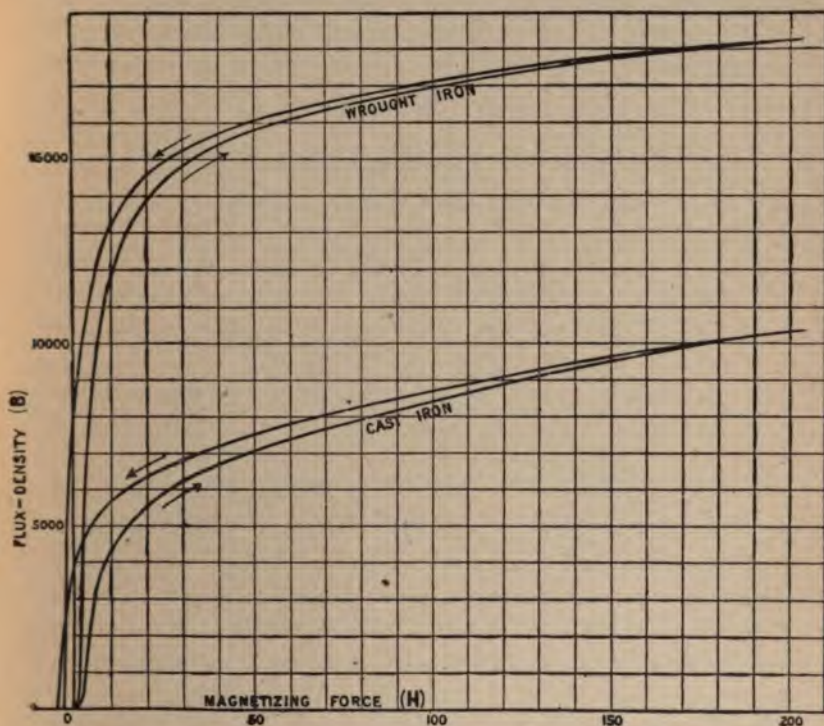


FIG. 83.—HOPKINSON'S CURVES OF MAGNETIZATION OF IRON.

designing dynamos it is convenient to have for reference a series of curves such as Fig. 84, made by observation on samples of the same iron as it is intended to use in construction.

In Fig. 84 are given seven curves,¹ relating to soft iron, hardened iron, "mild steel,"² annealed steel, hard-drawn steel, cast iron and glass-hard steel.

¹ *Phil. Trans.*, 1885. ² See p. 127 as to the nature of so-called "mild steel."

If we plot a curve taking the permeability $\frac{B}{H}$, or, as it is usually denoted, μ , for ordinates, and B for abscissæ, we have the results in a more convenient form for reference when making calculations of magnetic reluctances. Fig. 85 gives curves of various materials plotted in this way. The curve marked annealed soft iron is plotted from results obtained by Hopkinson from a carefully annealed specimen of soft iron. The value for B , μ and H for this specimen are given in square centimetre units in Table I., and in square inch units in Table II.

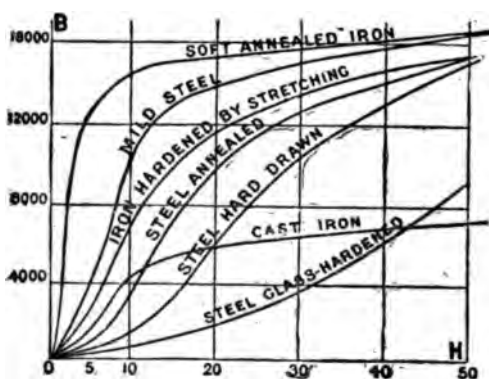


FIG. 84.—CURVES OF MAGNETIZATION OF VARIOUS SORTS OF IRON.

This curve is characteristic of the behavior of the best Swedish iron. Beneath is a curve given by Prof. D. C. Jackson,¹ showing the average results obtained from three specimens of good quality merchant wrought iron having the following percentage of impurities: $C = 0.075$, $Si = 0.1$, $Mn = 0.25$, $P = 0.1$, $S = 0.1$. It will be seen that with wrought iron the permeability, for small flux-densities, is not very great, but increases as the density is increased up to about 5000. An increase beyond this point decreases the permeability until when $B = 16,000$ the permeability has fallen to 400, and at $B = 20,000$ it is about 100. Thus it is not economical to push B much beyond 16,000. In dynamo field-magnets B is generally somewhere about 16,000, so that

¹ *Electromagnetism and the Construction of Dynamos* (Macmillan).

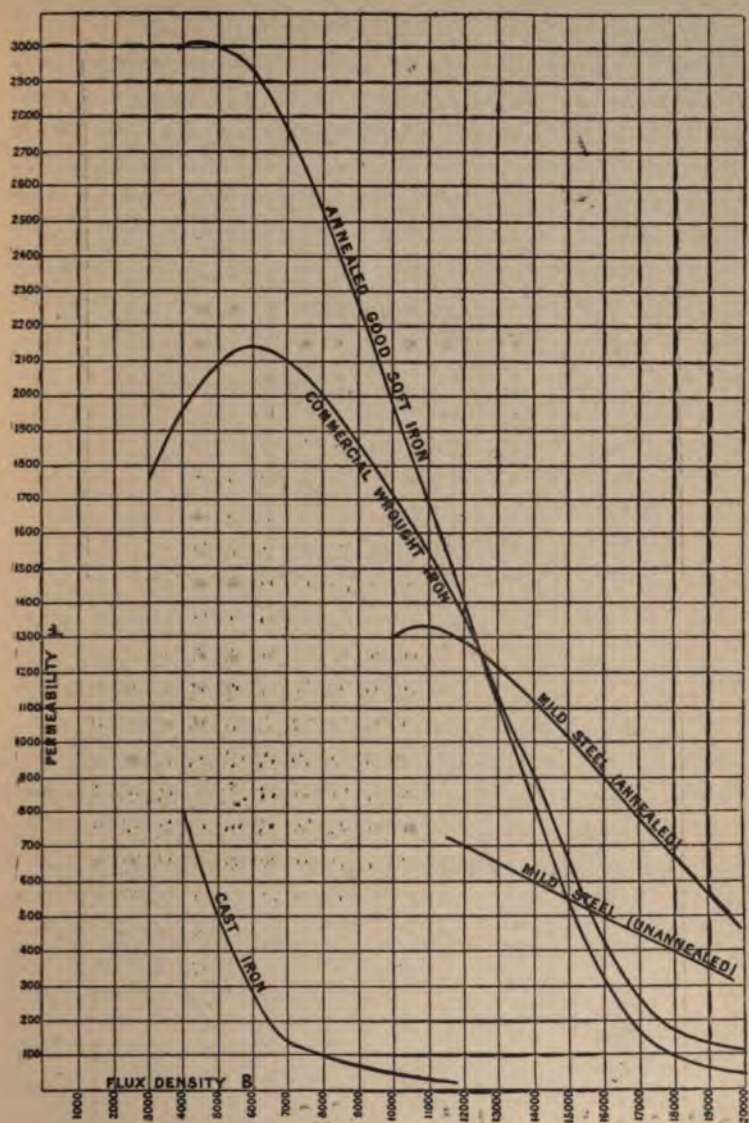


FIG. 85.—CURVES CONNECTING FLUX-DENSITY AND PERMEABILITY IN VARIOUS MATERIALS.

TABLE I. (SQUARE CENTIMETRE UNITS).

Annealed Wrought Iron			Gray Cast Iron.		
B	μ	H	B	μ	H
5,000	3000	1.66	4,000	800	5
9,000	2250	4	5,000	500	10
10,000	2000	5	6,000	279	21.5
11,000	1692	6.5	7,000	133	42
12,000	1412	8.5	8,000	100	80
13,000	1083	12	9,000	71	127
14,000	823	17	10,000	53	188
15,000	526	28.5	11,000	37	292
16,000	320	50			
17,000	161	105			
18,000	90	200			
19,000	54	350			
20,000	30	666			

TABLE II. (SQUARE INCH UNITS).

Annealed Wrought Iron.			Gray Cast Iron.		
B _s	μ	H _s	B _s	μ	H _s
30,000	2926	10.2	25,000	838	30
40,000	2857	14	30,000	445	53.5
50,000	2392	20.9	40,000	245	163
60,000	2166	27.7	50,000	112	447
70,000	1750	40	60,000	64	940
80,000	1368	63	70,000	40	1750
90,000	856	105			
100,000	407	245			
110,000	161	686			
120,000	64	1850			
130,000	28	4500			
140,000	18	7630			

the permeability of the material at this point is the criterion of the value of different materials for field-magnets. Now, looking at the curve for *mild cast steel*, it will be seen that, though the permeability for flux-densities of the order of 10,000 is very much lower than the permeability of iron, yet at great flux-densities the mild steel is equally good or even better than wrought iron. Being much cheaper, it has come very much into use in dynamo construction. Though this material is known as mild steel,¹ it is in reality much more allied to iron in its composition, as it contains only about 0.2 per cent. of carbon and is incapable of taking a temper. The facts that it can be cast and is soft to tool greatly facilitate the construction of dynamo frames of mild steel. *Mitis metal*, which is a sort of cast wrought iron, being a wrought iron rendered fluid by addition of a small percentage of aluminium, is, as the author has found, more magnetizable than cast iron, and not far inferior to the best wrought iron.

Hammering, rolling, chilling, or any process which tends to physically harden iron will lessen its permeability, but the evil effects of such processes may be destroyed by raising the metal to a red heat and allowing it to cool very slowly. The effect of this annealing is shown in the curves.

The curve for cast iron varies a great deal with the quality. Generally speaking, the permeability is decreased in proportion to the amount of carbon present in the combined state.

For an account of the various methods of measuring² the

¹ For data upon mild steel and mitis metal, see G. Henrard, *La Lumière Electrique*, xxxiii. 595; and Thompson, Knight and Bacon, *Amer. Inst. Elec. Engs.*, ix. June 7th, 1892.

² Consult also the following works:—

Ewing, J. A., various papers in the *Philosophical Transactions* of the Royal Society in the years 1885 to 1894. A full résumé is given in his book *Magnetic Induction in Iron and other Metals*. London, 1894.

Hopkinson, Dr. J., papers in the *Philosophical Transactions* of the Royal Society, 1885 to 1895. Those of chief importance are reprinted in his book.

Du Bois, H. J. G., *Magnetische Kreise, deren Theorie und Anwendungen*. Berlin, 1894.

Jackson, Dugald C., *Electromagnetism and the Construction of Dynamos* (Macmillan).

magnetic qualities of iron, see the author's treatise on *The Electromagnet*.

This is not the place to enter upon the modern molecular theory of magnetism propounded by Ewing. Those who would follow out this most important topic must refer to Ewing's published works.

EFFECTS OF AIR-GAP IN MAGNETIC CIRCUIT.

All the preceding results refer exclusively to that which goes on in iron itself, the curves of magnetization referring to the magnetic materials only. But if there is an air-gap in the

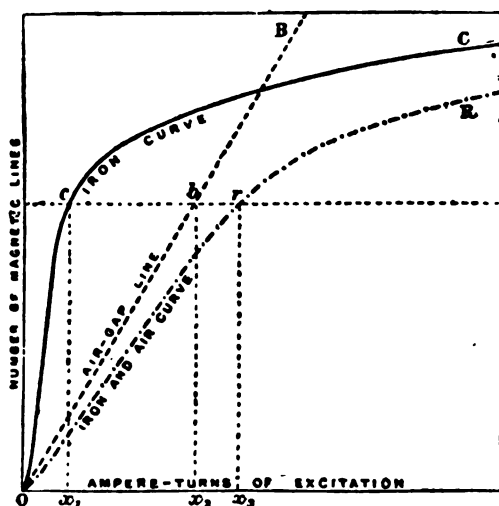


FIG. 86.—CURVE OF MAGNETIZATION OF MAGNETIC CIRCUIT WITH AIR-GAP.

magnetic circuit, or a gap filled with any non-magnetic material (possessing a permeability = 1), it is evident that to force the same number of magnetic lines across a layer of such inferior permeability will necessitate an increase in the magneto-motive-force that must be applied.

This is made plainer by reference to Fig. 86, in which the curve O c C represents the relation between the number of

magnetic lines in an iron bar and the number of ampere-turns of excitation ($H l \div 1.257$) needed to force this flux through the iron. For example, to reach the height c , the excitation has to be of the value represented by the length $O x_1$. On the same diagram the line $O b B$ represents the relation between the magnetic flux across the air-gap and the ampere-turns required to force this flux across. If the gap were 1 cm. long, 0.795 ampere-turns of current would produce field $H = B = 1$. In this case the gap is supposed to be shorter than 1 cm., the line sloping up at such a slope that the length $O x_2$ represents the ampere-turns requisite to bring up the magnetic flux to b , which is at the same height on the scale as c . It is then easy to put the two things together, for the total amount of excitation required to force these magnetic lines through air and iron will (neglecting leakage) be the sum of the separate amounts. The point x_3 is chosen so that $O x_3$ is equal to the sum of $O x_1$, and $O x_2$, or that the distance of point r from the vertical axis is equal to the sum of the respective distances of c and b . If the same thing is done for a large number of corresponding points, the resultant curve $O r R$ may be constructed from the two separate curves. It will be seen then that, in general, the presence of a gap in the magnetic circuit has the effect of causing the magnetic curve to rake over, *the initial slope being determined by the air-gap.*

EFFECT OF JOINTS.

Being now in a position to calculate the additional magnetizing power required for forcing magnetic lines across an air-gap, we are prepared to discuss a matter that has been so far neglected, namely, the effect of joints in the iron on the reluctance of the magnetic circuit.

It is a matter purely for experiment to determine how far a transverse plane of section across the iron obstructs the flow of magnetic lines. This matter has been examined by Professor J. J. Thomson and Mr. Newall in the Cambridge Philosophical Society's *Proceedings*, in 1887; and more fully by Professor Ewing, whose researches are published in the

Philosophical Magazine for September 1888. Ewing not only tried the effect of cutting and of facing up with true plane surfaces, but used different magnetizing forces, and also applied various external pressures to the joint. For our present purpose we need not enter into the questions of external pressures, but will summarize in Table III. the results which Ewing found when his bar of wrought iron was cut across by section planes, first into two pieces, then into four, then into eight. The apparent permeability of the bar was reduced at every cut.

TABLE III.—EFFECT OF JOINTS IN WROUGHT-IRON BAR (not compressed).

H	B				Mean thickness of equivalent air-space for one cut.		Thickness of iron of equivalent reluctance per cut.	
	Solid.	Cut in Two.	In Four.	In Eight.	Centi-metres.	Inches.	Centi-metres.	Inches.
7.5	8,500	6,900	4,809	2,600	0.0036	0.0014	4	1.57
15	13,400	11,550	8,900	5,550	0.0030	0.0012	2.53	1
30	15,350	14,550	12,940	9,800	0.0020	0.0008	1.10	0.433
50	16,400	15,950	15,000	13,300	0.0013	0.0005	0.43	0.169
70	17,100	16,840	16,120	15,200	0.0009	0.0004	0.22	0.087

Suppose we are working with the magnetization of our iron pushed to about 16,000 lines to the sq. cm., referring to Table III., we see that each joint across the iron offers as much reluctance as would an air-gap 0.0005 of an inch in thickness, or adds as much reluctance as if an additional layer of iron about $\frac{1}{800}$ th of an inch thick had been added. With small magnetizing forces the effect of having a cut across the iron with a good surface on it is about the same as though you had introduced a layer of air $\frac{1}{800}$ th of an inch thick, or as though you had added to the iron circuit about 1 inch of extra length. With large magnetizing forces, however, this disappears, probably because of the attraction of the two surfaces across that cut. The stress in the magnetic circuit, with high magnetic forces running up to 15,000 or

20,000 lines to the sq. cm., will of itself put on a pressure of 130 to 230 lbs. to the square inch, and so these resistances are considerably reduced; they come down in fact to about $\frac{1}{20}$ th of their initial value.

The above results of Ewing's are further represented by the curves of magnetization drawn in Fig. 87. When the

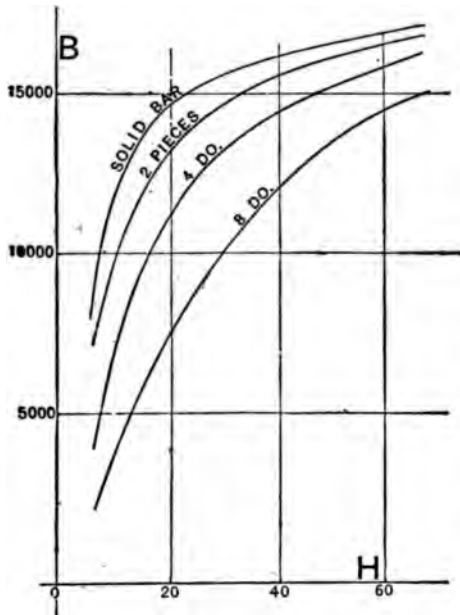


FIG. 87.—EWING'S CURVES FOR EFFECT OF JOINTS.

faces of a cut were carefully surfaced up to true planes, the disadvantageous effect of the cut was reduced considerably, and under the application of a heavy external pressure almost vanished.

EFFECTS OF HEAT.

When iron in a strong magnetic field is raised to a temperature above 600° C. it begins to lose its magnetic qualities, and at 780° C. they entirely disappear. At temperatures between 0° and 100° the effect of heat is so small that for all practical purposes it may be neglected.

RESIDUAL MAGNETISM.

It is well known that several kinds of magnetic materials—lodestone, steel, particularly hardened steel, and hard sorts of iron—exhibit residual magnetism after having been subjected to magnetic forces. It is also known that closed circuits of soft iron—even of the very softest—will exhibit a considerable amount of residual magnetism so long as the circuit which they constitute is unbroken. A very simple illustration of this is afforded by any electromagnet possessing in its core and well-fitting armature a compact magnetic circuit. If it is excited by passing a current, which is then quietly turned off, the armature usually does not drop off, and may even require considerable force to detach it; but when once so detached will not again adhere, the residual magnetization having almost entirely disappeared. In like manner a steel horse-shoe magnet, if magnetized powerfully while its keeper is across its poles, may become “supersaturated”; that is to say, magnetized to a higher degree of magnetization than it can retain in permanence, a portion of this residual magnetization disappearing the first time the keeper is removed.

Reference to Fig. 83 will show that when the magnetizing force H is gradually increased from zero to a high value, and is then gradually decreased to zero, the resulting internal magnetization B first increases to a maximum, and then decreases, but does not come back to zero. The curve descending from the maximum does not coincide with the ascending curve. In fact, when the magnetizing force has been entirely removed there remained (in this specimen) a residual magnetization of about 47,000 lines to the sq. in., or about 7300 lines per sq. cm. It has been proposed to give the name of the *remanence* to the number of lines per sq. cm., that thus remain as the residual value of B . To remove this *remanence*, a negative magnetizing force must be applied. Suppose enough magnetizing force has been used, the curve will descend and cut the horizontal axis at a point to the left of the origin; and with greater negative magnetizing forces,

the specimen will begin to be magnetized with magnetic lines running through it in the reversed direction. The particular value of the negative magnetizing force which is needed to bring the remanent magnetization to zero has been termed by Hopkinson the *coercive force*. In the specimen of wrought iron in question the coercive force (in C.G.S. measure) is about 2. The force thus required to deprive any specimen of its remanent magnetization may be taken as a measure of the tendency of iron of this particular quality to retain permanent magnetism. Hard kinds of iron and steel always show more coercive force than soft kinds of iron. For example, whilst that of soft wrought iron is about 2, that of hard steel may be as much as 50.

HYSTERESIS.

Professor Ewing, who has particularly studied the residual effects exhibited by various qualities of iron and steel, has given the name of *hysteresis* to this tendency of the effects to lag, in phase, behind the causes that produce them. The appropriate mode of studying hysteresis is to subject the specimen to a complete cycle (or to a number of successive cycles) of magnetizing forces. For example, let the magnetizing force begin at zero, and increase to a high value (say to $H = 200$) and then decrease back to zero, then reverse and increase to a high negative value, and finally return to zero. Such a cycle is given in Fig. 88, which is taken from Ewing's researches, and relates to a series of experiments made with a piece of annealed steel pianoforte wire. The curve begins in the centre of the diagram, and as H is increased positively, the curve rises at first concavely to the right, then turns over, and when $H = 90$, B has risen to a little over 14,000. When H is then reduced back to zero the curve turns back on itself, but does not fall as fast as it previously rose, for when H is reduced to 20, B has gone down only to 12,000, and when $H = 0$ the remanence is about 10,500. If at this point H had been again increased to 90, B would have run up again to 14,000, as shown by the thin line. If, however, the magnetizing force is reversed, the curve descends to the left, and

cuts the horizontal axis at -24 , which is therefore the value of the coercive force. On increasing the reversed magnetizing force to $H = -90$, the reversed magnetization increases to the value $B = -14,000$, or a little more. Then when these reversed magnetizing forces are reduced to zero, the curve returns towards the right, crossing the vertical axis at $B = -10,500$ (the negative remanence); and on re-reversing the magnetizing force it is found that when $H = +24$, the

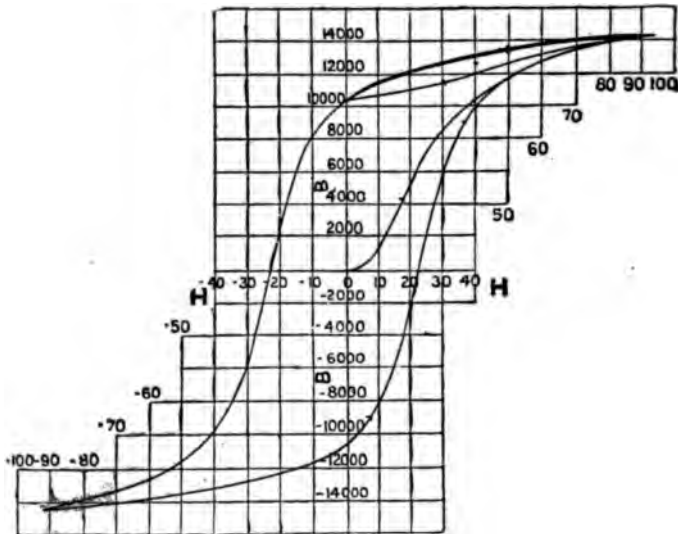


FIG. 88.—CYCLE OF MAGNETIC OPERATIONS ON ANNEALED STEEL WIRE.

magnetization is once more zero. After this point, increasing H causes the magnetization to run up very rapidly, not quite following its former track, but coming up as before to the apex, when H is raised to the same maximum of 90.

CYCLES OF MAGNETIZATION.

Such cycles of magnetization as that which has just been described, if carried out on any specimen of iron or steel, always yield curves that exhibit, like Fig. 88, an enclosed

area. This fact has been shown by Warburg¹ and by Ewing² to possess a special significance for the area enclosed is a measure of the work wasted, per unit of volume of the iron, in carrying the iron through a complete cycle of magnetiza-

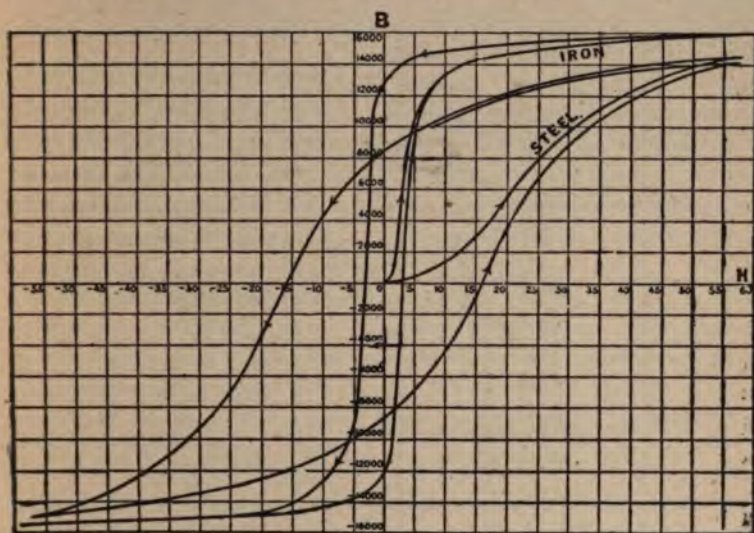


FIG. 89.—HYSTERESIS IN WROUGHT IRON AND IN STEEL.

tions. Just as the area traced out on the indicator-card of a steam engine is a measure of the heat transformed into useful work in the cycle of operations performed by the engine, so in this magnetic cycle the area enclosed by the curve is a measure of the work transformed into (useless) heat.³

¹ *Wied. Ann.*, xiii. 141, 1881.

² *Proc. Roy. Soc.*, xxxi. 22, 1881; xxxiv. 39, 1884; and xxxv. 1, 1885; and *Phil. Trans.*, 1885, pt. ii. 523.

³ The proofs of these matters are as follows. In a magnetic field of strength H it will require H units of work to move a unit of magnetism along a length of 1 centimetre against the magnetizing forces. Hence, since there are 4π magnetic lines to each unit of magnetism, the work done in one complete cycle on a single cubic centimetre of the iron will

be equal to $\frac{1}{4\pi} \int H dB$. If H and B are in C.G.S. units, the work will

be given in ergs per cubic centimetre. Hence if this number is multiplied by the number of cycles per second and divided by 10^7 , the result will express the number of watts of power wasted.

For the sake of comparison, a curve for wrought iron and one for steel are given side by side in Fig. 89. In all these cases the closed area represents the work which has been wasted or dissipated in subjecting the iron to these alternate

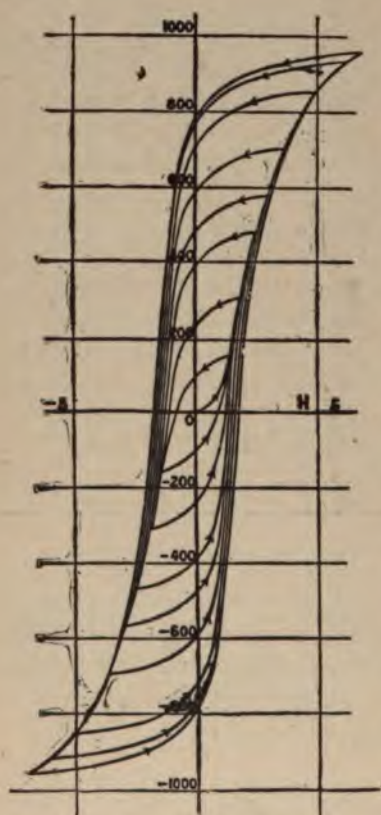


FIG. 90.—SUCCESSIVE CYCLES OF INCREASING AMPLITUDES.

graded series of reversals beginning with weak forces, and gradually increasing the force until the limits of H were ± 7 C.G.S. As the amplitude of the cycle is increased the area of the cyclic curve increases in a greater ratio—in other

magnetizing forces. In very soft iron, where the ascending and descending curves are close together, the enclosed area is small; and as a matter of fact, very little energy is dissipated in a cycle of magnetic operations. On the other hand, with hard iron, and particularly with steel, there is a great width between the curves, and there is great waste of energy. The energy lost per cycle depends not only upon the nature of the material but also upon the degree to which the magnetization is carried in each cycle—in fact, upon the *amplitude* of the cycle.

Fig. 90, taken from J.A.Ewing's researches,¹ shows the effect of subjecting a piece of soft annealed iron wire to a

¹ *Phil. Trans.*, 1885, p. 555.

words, the loss of energy per cycle is more than proportionally great when B is increased.

Mr. C. P. Steinmetz¹ has given the following law connecting the hysteresis loss h in ergs per cubic centimetre of iron per cycle and the flux-density B . He finds that

$$h = \eta B^{1.6}$$

where η is a constant called the hysteretic constant depending upon the kind of iron. This law is true for cycles performed either slowly or as rapidly as 200 per second. The following table gives the hysteretic constant η for different materials² when ordinary frequencies are employed.

HYSTERETIC CONSTANTS FOR DIFFERENT MATERIALS.

Material.	Hysteretic Constant η .	Material.	Hysteretic Constant η .
Very soft iron wire	·002	Soft annealed cast steel . .	·008
Very thin soft sheet iron . .	·0024	Soft machine steel	·0094
Thin good sheet iron	·003	Cast steel	·012
Thick sheet iron	·0033	Cast iron	·016
Most ordinary sheet iron . .	·004	Hardened cast steel	·025
Transformer cores	·0045		

From experiments with actual transformer plates at n cycles per second the hysteretic loss in watts per cubic centimetre of iron was found to be

$$W = 0.0033 \times 10^{-7} \times n \times B^{1.6}.$$

Besides the hysteretic loss in transformer plates, there is also a loss due to eddy currents in the iron. This varies as the square of the thickness of the iron, the square of the frequency, and the square of the flux-density. Fleming has obtained by calculation the formula

$$Y = X^2 B^2 n^2 10^{-16},$$

¹ *Amer. Inst. Elec. Engineers*, Jan. 19th, 1892; *Electrician*, Feb. 12th, 19th and 26th, 1892.

² For particulars of Ewing's Magnetic Tester for measuring Hysteresis in sheet iron, see *Inst. Elec. Engineers*, April 25th, 1895, also *Electrician*, xxxiv. 786.

Y being the loss in watts per cubic centimetre of core made up of the strip, and X being the thickness of the strip in mils. Thus we have the total loss in watts due to both hysteresis and eddy currents—

$$W = 0.0033 \pi B^{1.6} \times 10^{-7} + X^2 B^2 n^2 \times 10^{-16}.$$

This has been found to agree very closely with practice.

If, as in a transformer, the iron is carried through a certain number of cycles per second, we have a continual loss which

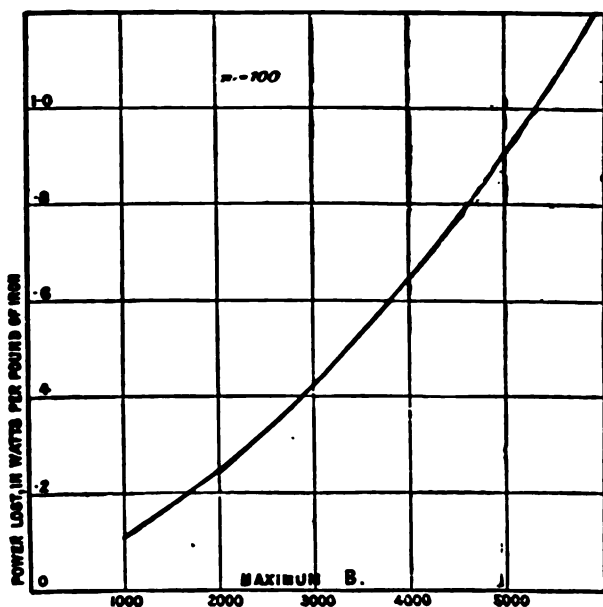


FIG. 91.

can be measured in watts per lb. of iron, for the amount of waste depends upon the quantity of iron magnetized.

Plotting the loss in watts per lb. of iron with the maximum flux-density B, the curve¹ (Fig. 91) shows an ever increasing slope. From this it appears that it is not economical to carry B to a very high value in transformers. The most economical value depends upon a variety of circumstances

¹ Kapp, *Journ. Inst. Elec. Engineers*, xxiii. 207, 1894.

such as the frequency of supply, the amount of waste allowable, and the first cost of the transformer. A flux-density of 4000 is very usual. It must be remembered that by increasing the flux-density we can decrease the cross-section of the iron, and thus the total weight of iron employed, and this up to a certain point reduces the loss, although the loss per pound is increased. Another inducement to increase the flux-density in a transformer is the fact that for very small flux-densities the permeability of the iron is less than for the flux-densities of about 7000. The curve in Fig. 92 shows how the per-



FIG. 92.—PERMEABILITY CURVE FOR TRANSFORMER-IRON.

meability of transformer-iron increases, as the flux-density is increased up to about 7000; after this point the curve is flat, and then descends again as higher densities are reached. This fact can indeed be seen from the curves in Fig. 90, for the slope of a line joining the peak of any cyclic curve to the origin gives the permeability of the iron for that cycle so far as it affects the magnetizing current required in a transformer. By increasing the permeability we make a considerable saving in the energy required to magnetize.

The following table gives the number of watts wasted by

hysteresis in well-laminated soft wrought iron when subjected to a succession of rapid cycles of magnetization.

WASTE OF POWER BY HYSTERESIS.

B	B _r	Watts wasted per cubic foot at 10 cycles per second.	Watts wasted per cubic foot at 100 cycles per second.
4,000	25,800	40	400
5,000	32,250	57.5	575
6,000	38,700	75	750
7,000	45,150	92.5	925
8,000	51,600	111	1110
10,000	64,500	156	1560
12,000	77,400	206	2060
14,000	90,300	262	2620
16,000	103,200	324	3240
17,000	109,650	394	3940
18,000	116,100	487	4870

Ewing has given the following values of the energy wasted in a magnetic cycle of a strong magnetization on various brands of iron and steel:—

WASTE OF ENERGY BY HYSTERESIS.

Brand experimented upon.	Ergs per cubic centimetre lost in one complete cycle of magnetization.
Very soft annealed iron	9,300
Less soft " "	16,300
Hard drawn iron wire	60,000
Annealed steel wire	70,500
Glass hard steel wire	76,000
Pianoforte steel wire (ordinary state)	116,000
" " (annealed)	94,000
" " (glass hard)	117,000

Hopkinson found that oil-hardened tungsten steel, the sort chosen for making permanent magnets because of its great

coercive force, wasted no less than 216,864 ergs per cubic cm. per cycle. He has pointed out that the area of a curve like Fig. 88 is approximately equal to a rectangle, the height of which is double the remanence, and the breadth of which is double the coercive force.

Ewing has shown that vibration tends to destroy residual effects. Also Dr. Finzi has found¹ that iron cores whilst traversed by an alternating electric current show no hysteresis, the ascending and descending curves of magnetization coinciding. There is also some evidence that with very rapid frequencies there is less work wasted per cycle than there would be in the same cycle performed slowly.

When an armature core is rotated in a strong magnetic field the magnetization of the iron is being continually carried through a cycle, but in a manner quite different from that in which it is carried when the magnetizing force is periodically reversed, as in the core of a transformer. Mordey has found² the losses by hysteresis to be somewhat smaller in the former case than in the latter.

Magnetic Creeping.—Another kind of after-effect was discovered by Ewing, and named by him “viscous hysteresis.” This is the name given to the gradual creeping up of the magnetization when a magnetic force is applied with absolute steadiness to a piece of iron. This gradual creeping may go on for half-an-hour or more, and amount to several per cent. of the total magnetization. This is a true, but slow, magnetic lag, and must not be confounded either with the lag of phase discussed already under the name hysteresis, or with the apparent lag due to the retardation of the magnetizing current resulting from self-induction, or with the apparent lag observable in unlaminated iron cores due to eddy-currents circulating in the mass of the iron itself.

Retardation of Magnetization.—It has long been known that in solid cores of electromagnets the rise and fall of the magnetism is retarded by eddy-currents in the iron, the outside part of the iron becoming magnetized first when the current is

¹ *Electrician*, xxvi. 72, April 3, 1891.

² See also Ewing, in *Electrician*, xxvii. 602, 1891.

turned on ; whilst the magnetism of the inner parts grows up later when the eddy-currents in the outer part die away. There is thus a regular penetration or propagation of the magnetism from the outer to the inner parts of the core. When the magnetizing-current is cut off the inner part is the last to lose its magnetism. In large dynamos many minutes may elapse before the magnetism attains its maximum. For this reason the author pronounced it useless to put a compound winding upon dynamos with large solid electromagnets for use as electric railway generators. It is even possible for the mid-core of an electromagnet to have a magnetization of reverse direction to that of the outer layers. The phenomenon of magnetic retardation in solid cores has lately been investigated by Dr. J. Hopkinson and Mr. E. Wilson,¹ using an iron-clad electromagnet with a core 12 inches in diameter with exploring coils buried at different depths in its substance. Hopkinson showed that the retardation varies as the square of the linear dimensions. He also investigated the effect when the magnetizing force was alternated in periodic cycles, and found that the depth to which the magnetizations penetrate depends upon the frequency (see Chapter XXII.).

Slow changes in the Magnetic Properties of Iron.—When iron is magnetized for a long time by rapidly alternating currents, its magnetic properties undergo a slight change, so that the amount of energy absorbed in carrying it through a given magnetic cycle is increased. This effect has been observed in connection with the working of transformers on alternate-current systems, and is due to a physical change in the iron, which affects its permeability or its hysteresis loss, or both. Whether the change is due directly to the continual reversal of magnetization or whether it is a secondary effect caused by the heating, and by the compression that takes place with the expansion of the iron through heat, is not certainly established, but a series of experiments carried out by Mr. W. M. Mordey,² point to the latter cause as being sufficient to account for the phenomenon.

¹ *Journ. Inst. Elec. Engineers*, Feb. 1895, and *Philos. Trans.*, 1895.

² *Proc. Roy. Soc.*, lvii. 1894.

APPROXIMATE FORMULÆ FOR THE LAW OF THE
ELECTROMAGNET.

Before the discovery of the law of the magnetic circuit, many attempts were made to find a working formula to express the amount of magnetism which is produced in a given electromagnet by an exciting current of any particular value. Of these an elaborate account is given in the second and third editions of this book. As they are not now used in dynamo designing, they may be very briefly dismissed.

The earliest suggestion of Lenz and Jacobi was a simple proportion between the exciting current and the magnetism produced. This is equivalent to saying that the curve of magnetization is a straight line sloping upwards from the origin. Joule showed that this law was not true; that with sufficient magnetizing power saturation set in. Müller (followed by Von Waltenhofen, Kapp and others) proposed an arc-tangent formula; suggesting that if the exciting current be represented by the length of a straight line drawn as a tangent to a circle, then the arc which it subtends will represent the amount of magnetism which results. This gives a saturation limit, but fails to represent the facts in the earlier stages of magnetization. Lamont, from theoretical considerations, proposed an exponential formula, from which he deduced an approximate expression equivalent to the statement that the permeability is at all stages proportional to the difference between the actual amount of magnetism and its possible maximum amount. Lamont's formula was revived by Frölich,¹ and largely used in various forms by various writers, including the author of this book. Let us make the supposition that the magnetic flux N will have at complete saturation a maximum value $\bar{N}$, and that the magnetizability of the magnet at any stage is proportional to the room left for magnetic lines, that is to $\bar{N} - N$. Now, writing S for the number of spirals and C for the current flowing in them, we get SC for the ampere-turns of exciting power, and $N \div SC$ will be the ratio of magnetism to magnetizing power or magnetizability. We may then write

$$\frac{N}{SC} = \frac{\bar{N} - N}{h},$$

¹ *Elektrotechnische Zeitschrift*, pp. 90, 139, 170, 1881, and p. 73, 1882. See also Dr. Frölich's book, *Die dynamoelektrische Maschinen*, Berlin, 1886

where k is a constant of the particular electromagnet. By simple transformation this equation becomes

$$N = \bar{N} \frac{SC}{SC + k},$$

and it is clear that the meaning of k is that particular number of ampere-turns which will reduce the magnetizability to half its initial value, or will bring up the magnetism to half-saturation.

This number of ampere-turns the author named the *diacritical* number, and the number producing half-saturation he called the *diacritical* current. Dr. Frölich has independently made use of his conception, and has applied it in his formula for dynamos. The argument is his: the notation here used is, however, the author's.

This formula, though it does not take into account the difference between ascending and descending magnetizations, is quite good enough to serve as a first approximation, and is therefore useful. As pointed out by Fleming¹ and by Kennelly,² the justification of it is to be found in the circumstance that the reluctivity (or reciprocal of the permeability) is very nearly a simple linear function of H .

MAGNETIC UNITS.

While these pages are going through the press the Standards Committee of the British Association has proposed the adoption of a unit of magnetic flux under the name of the *weber*, equal to 10^9 magnetic lines of the C.G.S. system. The *line* is itself a unit of magnetic flux; but is too small to be convenient in many cases as a unit. But the multiples *kiloline* for one thousand lines, and *megaline* for one million lines are terms which have been found convenient by dynamo designers. One *weber* is therefore equal to 100 megalines. This magnitude has been chosen to correspond to that of the *volt* (compare p. 170); so that a wire cutting 1 weber per second will have induced in it an electromotive-force of 1 volt. The Standards Committee also proposes the name *gauss* for the C.G.S. unit of magnetic potential; being equal to $10 \div 4 \pi$ of an ampere-turn. To convert ampere-turns into gaussess one must multiply by $4 \pi \div 10$, or by 1.257.

It should be remarked that the American Institute of Electrical Engineers has proposed the name *weber* to denote 1 line instead of 10^9 lines; and that it has proposed the name *gilbert* for the unit now called the *gauss*, while it has, unfortunately, proposed the term *gauss* as the name of a unit of flux-density to mean a density of 1 line per square centimetre.

¹ *Journ. Inst. Elec. Engineers*, xv. 570, 1886.

² *Electrical World*, xvii. 358, 1891.

CHAPTER VII.

THE MAGNETIC CIRCUIT.

KNOWING the magnetic properties of the materials with which we have to deal, we are in a position to calculate the number of ampere-turns necessary to produce the desired flux in the magnetic circuit of a dynamo of any given shape and dimensions. The magnetomotive-force M , which is equal to 1.257 times the ampere-turns $C S$, depends upon the reluctance R of the circuit, and the amount of flux N required. We in fact have the general equation

$$M = N R.$$

But as the total reluctance is made up of the reluctances of various parts of the circuit in series with one another, and which do not necessarily carry the same amount of flux, it is convenient to consider the parts separately. Referring to Fig. 93, which gives a diagrammatic view of the magnetic circuit of a bipolar dynamo, we have three parts, namely an iron armature-core, the two air-gaps, and the iron field-magnets.

If the average length¹ of the path for the magnetic lines in the armature core is denoted by l_1 and the average sectional

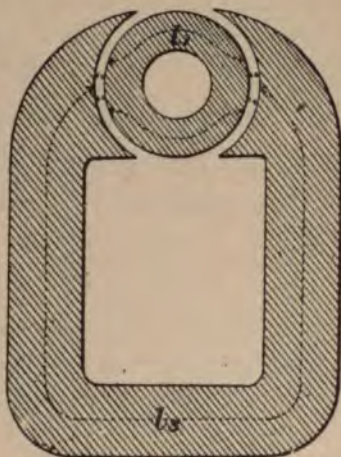


FIG. 93.

¹ For an example in the estimation of these lengths and areas, see p. 355.

area by A_1 and the permeability by μ_1 , the reluctance of the core will (see p. 119) be $\frac{l_1}{\mu_1 A_1}$. The total flux N through the armature divided by A_1 gives the flux-density B , so that μ_1 can be ascertained from the permeability curve of the material used. Then $\frac{N l_1}{\mu_1 A_1}$ gives the magnetomotive-force required to drive the flux through the armature core. Similarly $\frac{2 N l_2}{A_2}$ (where l_2 and A_2 are the length and area respectively of one of the air-gaps) gives the magnetomotive-force required to drive the flux through the two air-gaps. The flux through the field-magnets is greater than that through the armature, owing to magnetic leakage. As will be seen below we are able to express the average flux through the field-magnet in the form $v N$, where v is a number (generally about 1.3) which can be ascertained from the shape of the magnet (see p. 151). Having found the permeability μ_3 of the material of the field-magnet when carrying the flux $v N$ through the area A_3 , we can write $\frac{v N l_3}{\mu_3 A_3}$ for the magnetomotive-force required for this part of the circuit. Then the total ampere-turns required will be

$$SC = \frac{M}{1.257} = \frac{N}{1.257} \left\{ \frac{l_1}{\mu_1 A_1} + \frac{2 l_2}{A_2} + \frac{v l_3}{\mu_3 A_3} \right\}.$$

This method of calculation is substantially that proposed independently in 1886 by Drs. J. and E. Hopkinson, and by Mr. Kapp. But the Hopkinsons went much further in their investigation. They plotted a separate curve for the relation between the magnetomotive-force and the flux for each separate part of the magnetic circuit, and then summed up the separate curves so as to obtain a final resultant characteristic curve. This is done first on the assumption that there is no magnetic leakage; and after a first approximation has thus been obtained, the theoretical result is compared with the actual result of experiment, thereby affording a means of estimating the corrections that must be introduced.

As a matter of fact, the Hopkinsons stated their formula a little more generally. Instead of assuming the existence of μ for the different parts, they contented themselves with saying that the flux-density in each part must be some function of the magnetic force acting in that part. Now, if there be a flux of N magnetic lines passing through area A square centimetres, the flux-density B will be equal to N/A . Accordingly, we may write for the magnetomotive-force acting in the armature part of the magnetic circuit $f\left(\frac{N}{A_1}\right) \times l_1$, which "function" may be examined and plotted out as a curve. In fact the curves of magnetization, such as are given on p. 123, are nothing else than curves which show the relation between the magnetizing forces and the amount of magnetism they induce. There will be a similar expression $f\left(\frac{N}{A_3}\right) \times l_3$ for the magnetomotive-force that acts in the field-magnet part, whilst for the gaps the magnetomotive-force is simply $\frac{N}{A_2} \times 2 l_2$; for the function for air = 1. The whole or integral magnetizing force will be got by adding together the separate terms

$$l_1 f\left(\frac{N}{A_1}\right) + 2 l_2 \frac{N}{A_2} + l_3 f\left(\frac{N}{A_3}\right) = 4 \pi SC \div 10.$$

This mode of stating the matter has the following advantages:—(1) The use of the function of which the value is to be found by reference to a curve or tabulated set of observations (such as those given in the preceding chapters, instead of merely using the symbol μ , makes the expression more general; (2) the separate terms being differently affected by leakage of the magnetic lines, it is easy to apply corrections separately.

If then we plot out, separately, curves for each of the three terms, so as to show separately the numbers of ampere-turns required to drive different amounts of magnetic flux through each of the separate parts of the circuit, we may then combine them in a resultant curve. Having in this way built

up a curve characteristic of the magnetization, the Hopkinsons then proceeded to correct it by considering the leakage. They found that in the dynamo experimented upon (an Edison-Hopkinson) only about three-fourths of the magnetic lines created in the field-magnet actually passed through the armature-core, the rest leaking across either between the pole-pieces through the air or the bed-plate, or else turning back from the pole-pieces, to the yoke at the top. Experiment gave the ratio of the magnetic flux at a point half-way up the upright iron cores to the flux through the armature as 1.32. Let the symbol v stand¹ for this ratio. Then in the particular dynamo experimented on there was a yoke at the top through which the length of (curved) path was l_4 , and which had cross-section A_4 . There were also solid pole-pieces, for which the corresponding quantities were called l_6 and A_6 . Inserting these additional matters into the equation, it now becomes

$$l_1 f\left(\frac{N}{A_1}\right) + 2l_2 \frac{N}{A_2} + l_3 f\left(\frac{vN}{A_3}\right) + l_4 f\left(\frac{vN}{A_4}\right) + 2l_6 f\left(\frac{N}{A_6}\right) \\ = 4 \pi S C \div 10.$$

There are now five terms to be calculated, giving five curves (Fig. 94). Moreover, as is well known, with descending magnetizing forces the curve of magnetization is different from the curve with ascending magnetizing forces. Fig. 94, which is taken from the Hopkinsons' paper, shows how they plotted out both for ascending and descending magnetizations the five curves. Of these, A relates to the armature, B to the two interstitial gaps, C to the field-magnet cores, G to the yoke, and H to the two pole-pieces. To obtain the resultant curve the abscissæ at any particular level must be added together. For example: for a flux of 12 millions of magnetic lines, the air-gaps (curve B) required about 17,500 ampere-turns, the magnet-cores (curve C) 5000, the yoke (curve G) about 1000, and the armature (curve A) about 300, making a total of 23,800, which is accordingly plotted off to the right. The

¹ It can be determined experimentally, or calculated as hereafter shown.

resultant curve is swept through the points so calculated. The resultant ascending and descending curves are both shown. They agree remarkably well with the crosses and points which were plotted out from actual experiment. The

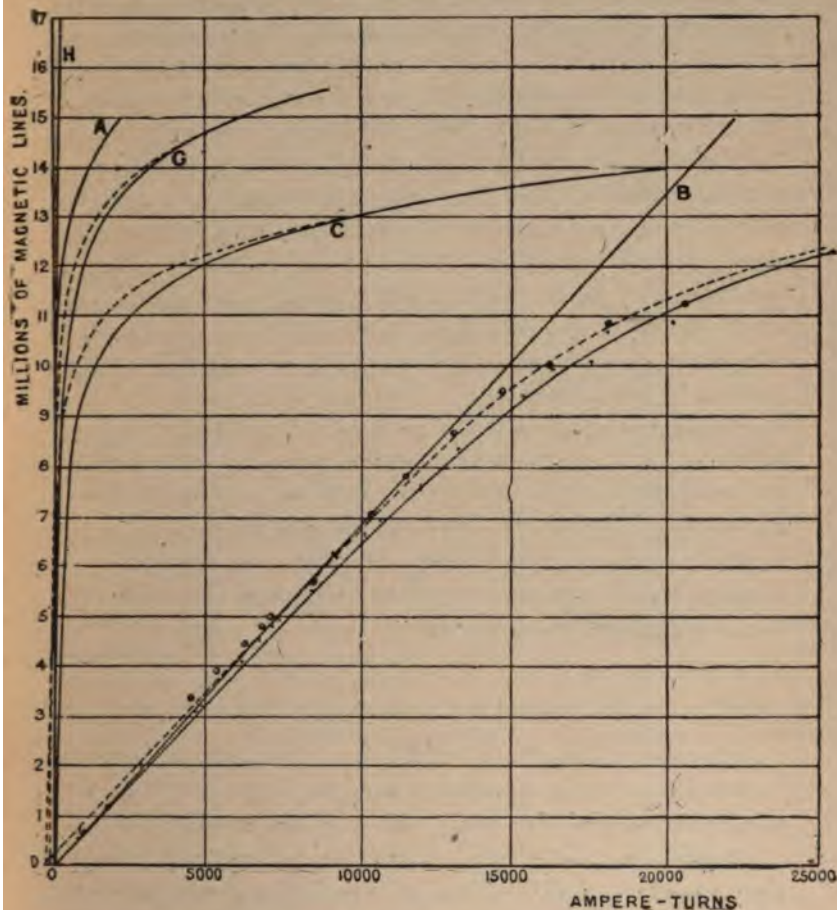


FIG. 94.

dotted curves and the crosses surrounded with circles relate to descending magnetizations. The student should not fail to consult the original paper.

The position of the magnetizing coils on the magnetic

circuit is a matter of some importance. The electric and magnetic circuits being interlinked wherever the coils are placed they will exert the same total magnetomotive-force, but it is well, in view of the occurrence of magnetic leakage, to place the coils as near as possible to that part of the magnetic circuit where the magnetomotive-force is required. As has been pointed out above (p. 119), when there are several coils, their magnetomotive-forces will only be added together if they are interlinked with the same magnetic circuit; and therefore when a double magnetic circuit is employed (as in a dynamo of the Manchester type, for instance), each branch of the circuit requires to be wound with sufficient ampere-turns to give the required difference of magnetic potential between the poles. Thus, other things being equal, twice as much power is wasted in the field-magnet. However, as the girth of each branch is less than the girth of a single circuit, it is not necessary to use quite twice as much copper in winding in order to have the same loss per coil. In cases where several magnetic circuits are required, as in a multipolar field-magnet, it is sometimes convenient to have only one magnetizing coil and interlink all the magnetic circuits with it; such an arrangement is shown in Fig. 425. It would even be possible to wind the magnetic circuit several times round the electric circuit.

LEAKAGE OF MAGNETIC LINES.

Whenever there exists a difference of magnetic potential between two points, a certain number of magnetic lines will pass from one to the other, whatever the medium between them may be. Thus, with a dynamo field-magnet between the poles of which it is necessary to maintain a high difference of magnetic potential a large number of lines will pass through the air from pole to pole, instead of going through the armature, leaking out sideways and constituting a *stray field*.

It should be borne in mind that magnetic leakage from the field-magnet of a dynamo does not cause any waste of energy except in so far as it necessitates a large number of ampere-

turns by increasing the flux-density, and therefore the drop in magnetic potential in the magnet core. In those cases where the reluctance of the iron core is very small as compared with other parts of the magnetic circuit, leakage does no harm. In field-magnets of alternators of the type shown in Figs. 377 and 425 the leakage is enormous, but it is of no consequence so long as the requisite difference of magnetic potential can be maintained between the poles without an undue expenditure of exciting current.

The ratio of total field to useful field is known as the *coefficient of leakage* and denoted by symbol v . The following are its values in sundry types of machines.

STRAY FIELD IN DIFFERENT DYNAMOS.

Name of Machine.	Field.	Armature.	Remarks.	Value of v .
Edison-Hopkinson	Bipolar	Drum	Poles next bed-plate	1.32
Edison (American)	Bipolar	Drum	Poles next bed-plate	1.4
General Electric Co.	Multipolar	Drum	Direct-driven	1.25
Kapp	Bipolar	Drum	Yoke next bed-plate	1.30
Siemens	Bipolar	Drum	Yoke next bed-plate	1.30
Manchester	Double Magnet, 2-pole	Long Ring	Bed and one pole cast together	1.49
Ferranti	Double Magnet, multipolar	Coreless Disk	Ordinary pattern (alternating)	2.00

In a series of machines of any given type, the leakage factor is less in the larger sizes. For instance, in the bipolar Edison dynamos it varies from 2.0 in the 100-watt machine to 1.20 in the 300 kilowatt machine. In large multipolar machines, with inward-pointing poles, the coefficient varies from 1.5 in a 2-kilowatt 4-pole machine to 1.15 in a 2000-kilowatt machine.

The stray field around a dynamo may be explored by moving a compass-needle about in it. A method of ex-

ploring the effect in the neighborhood of dynamos has been perfected by Messrs. Edser and Stansfield.¹ They found that the stray field immediately behind one of the poles of a Kapp bipolar dynamo had a value of about 300 C.G.S. units. At a distance of 5 inches away along a horizontal line at right angles to the shaft, it has fallen to 160, at 10 inches to 80, at 20 inches to 22, and at 30 inches to 5 units. Fig. 95 depicts the general direction of the magnetic lines that leak from an Edison-Hopkinson dynamo. It will be noted that leakage takes place in other ways than from pole to pole. There is a

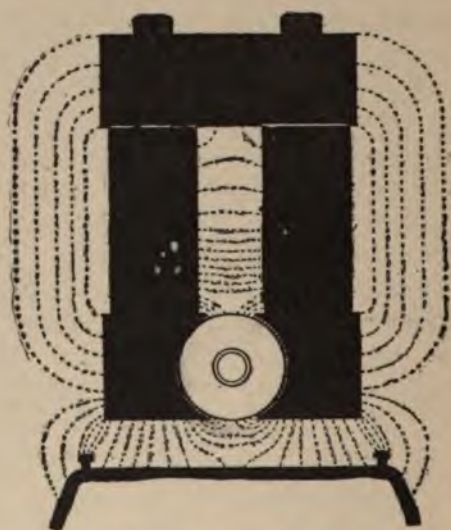


FIG. 95.—STRAY FIELD OF AN EDISON-HOPKINSON DYNAMO.

tendency for magnetic lines to leak from the pole-pieces to the yoke at the top. The cast-iron bed-plate being in proximity to the two poles (where the difference of magnetic potential is greatest) promotes leakage through itself, even though the machine is mounted on a zinc footstep.

Many machines have been examined as to their magnetic leakage by Carl Hering,² who also has given drawings of

¹ *Electrician*, xxix. 118, June 3, 1892.

² *Electrical Review*, xxi. 186 and 205, 1887.

them. An extraordinary case was found to be afforded by the stray field of the Thomson-Houston arc lighting dynamo (Fig. 311). The reader should also refer to some experiments by Carhart,¹ and to others by Trotter,² Wedding,³ Puffer,⁴ Mavor,⁵ and Wiener.⁶

It is evident that the leakage coefficient cannot be constant in a given machine, for the amount of leakage depends on the relative permeance of the path through the armature core and of the stray paths outside. Now the permeability of air is a constant, whilst that of the iron cores decreases as the degree of saturation is raised; so that the leakage increases with higher excitation. Also when a large current is drawn from the armature, the demagnetizing reaction of the armature current directly promotes leakage, as it raises an opposing magnetomotive-force in the direct path of the magnetic lines. Moreover, since leakage takes place more or less all over a magnet, it is clear that what we call the coefficient of leakage is only a sort of average.

By experiment we may determine the actual value of the leakage ratio in various parts. Drs. J. and E. Hopkinson did this for a "Manchester" dynamo,⁷ using exploring coils placed around the field-magnet of the dynamo in various positions. The number of magnetic lines which were thus enclosed was ascertained by suddenly cutting off the exciting current and noticing the resulting induction current in a suitable galvanometer. A still more complete examination was made by Lahmeyer⁸ on an iron-clad dynamo (Fig. 96). In this case six separate exploring coils, each having the same number of turns, were used. That surrounding the armature, enclosing the useful field, is called A, the others being numbered. The

¹ *Electrical Review*, xxv. 286; and *Electrician*, xxiii. 644, 1889.

² *Journal Inst. Electrical Engineers*, xix. 243, 1890.

³ *Elektrotechnische Zeitschrift*, xlii. 67, 1892.

⁴ *Electrical Review*, xxx. 487, 1892.

⁵ *Electrical Engineer*, xlii. 428, 1894. "New Points in Dynamo Design."

⁶ *Electrical World*, xxiv. 647, Dec. 22, 1894.

⁷ See their paper in *Phil. Trans.*, Part I. 331, 1886; and *Electrician*, xviii. 39, 63, 86 and 175, Nov. and Dec. 1886.

⁸ *Elektrotechnische Zeitschrift*, ix. 283, 1887.

deflexions obtained are given in column 2 of the following table. The maximum flux was found at 3. Taking this number as 100, the percentages of leakage at the coils are given in column 3. In column 4 are given the various fluxes,



FIG. 96.—EXPLORING THE MAGNETIC LEAKAGE OF A DYNAMO.

taking that through A as 100, and in column 5 the values of v at the various parts. It is clear that the yoke parts were of insufficient thickness.

A	780	10·9	100	1
I.	788·5	10·1	101	1·01
II.	861	1·6	110	1·10
III.	876	0	112	1·12
IV.	850	3·0	109	1·09
V.	749	14·5	96	0·96

In the case of the Edison-Hopkinson dynamo, the Hopkinsons give 1·32 for v , this being the ratio observed between the throw when the exploring coil was placed half-way up the magnet limbs and when it was placed around the armature. If the exploring coil had been placed higher up, and if the armature had been excited so as to exert a demagnetizing action, the leakage coefficient would have been found to be at least 1·4.

CALCULATION OF LEAKAGES.

It is possible to predetermine, from the working-drawings of a dynamo before it is built, the probable amount of leakage. Calculations of the leakage are based upon the principle that where a circuit offers alternative paths, the magnetic flux will divide itself between the paths in the proportion of their relative facility for flow, exactly as an electric current divides where there are alternative conducting paths. In fact, the law of shunts has been found to hold good for magnetic lines. The reader should consult the researches of Ayrton and Perry¹ on this point. It follows that along any branched path the joint permeance² (or magnetic conductance) will be the sum of the permeances of the separate paths. Hence, if the permeances of the separate paths of the useful and waste magnetic fluxes of a dynamo are known, the coefficient of allowance for leakage, v , can be calculated, it being the ratio of the total flux to the useful flux. Call the useful flux u and the wasteful flux w ; then

$$v = \frac{u + w}{u}.$$

But each of these is a complicated quantity; therefore the more complete formula is

$$v = \frac{u_1 + u_2 + u_3 + \dots + w_1 + w_2 + w_3 + \dots}{u_1 + u_2 + u_3 + \dots}$$

In order to determine the separate permeances along the various leakage paths, we must resort to some useful rules or lemmas originally suggested by Professor Forbes,³ which consist in certain approximate integrations. For the convenience of British engineers the values have been recalculated into inch measures instead of centimetre measures.

¹ *Journ. Soc. Teleg. Engineers and Electricians*, 530, 1886.

² *Permeance* is of course the reciprocal of magnetic reluctance; just as electricity conductance is the reciprocal of electric resistance.

³ *Journ. Soc. Teleg. Engineers*, xv. 551, 1886.

Rule I.—*Permeance between two parallel areas facing one another.* Assume (Fig. 97) that the magnetic lines are straight and equally distributed over the surfaces: then,

$$\begin{aligned}\text{Permeance} &= 3.1918 \times \text{mean area (square inches)} \div \text{distance} \\ &\quad \text{(inches) between them} \\ &= 1.596 \times (A_1'' \times A_2'') \div d''.\end{aligned}$$

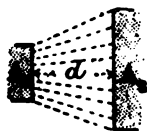


FIG. 97.

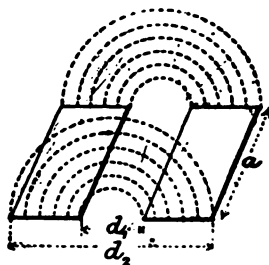


FIG. 98.

Rule II.—*Permeance between two equal adjacent rectangular areas lying in one plane.* Assuming (Fig. 98) lines of leakage to be semicircles, and that distances d_1'' and d_2'' between their nearest and furthest edges respectively are given; also a'' their width along the parallel edge:—

$$\text{Permeance} = 2.274 \times a'' \times \log_{10} \frac{d_2''}{d_1''}.$$

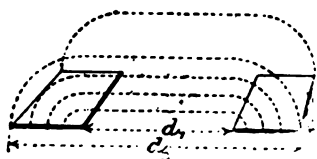


FIG. 99.

Rule III.—*Permeance between two equal parallel rectangular areas lying in one plane at some distance apart.* Assume (Fig. 99) lines of leakage to be quadrants joined by straight lines.

$$\text{Permeance} = 2.274 \times a'' \times \log_{10} \left\{ 1 + \frac{\pi (d_2'' - d_1'')}{d_1''} \right\}.$$

Rule IV.—*Permeance between two equal areas at right angles to one another.*

Permeance = double the respective values calculated by II.

If measures are given in centimetres these rules become the following:—

$$\text{I. } (\frac{1}{2} A_1 + A_2) \div d.$$

$$\text{II. } \frac{a}{\pi} \text{hyp. log. } \frac{d_2}{d_1}.$$

$$\text{III. } \frac{a}{\pi} \text{hyp. log. } \left(1 + \frac{\pi (d_2 - d_1)}{d_1} \right).$$

Using these rules to predetermine the leakage to fly-wheels, pedestals and shafts, it is possible from the working drawings to predict the performance of a machine to within 2 per cent.

The author has given (in his work on *The Electromagnet*) some further rules, including the case of leakage between two parallel cylindrical limbs.

In the fourth edition of the present work an example of the application of these rules to the calculation of the leakage of an actual dynamo was given in great detail.

CHAPTER VIII.

FORMS OF FIELD-MAGNETS.

WITH the principle of the magnetic circuit to guide him, the reader will have little difficulty in judging of the relative value of the various designs of field-magnets; for he will remember that the magnetic circuit of highest permeability will have the most compact form, greatest cross-section, softest iron, and fewest joints. In many cases, however, the structure which acts as magnet has also to do duty as a framework, involving other considerations. Theoretically it is better that the field-magnet of a simple 2-pole machine should be constituted of a single magnetic circuit than of two (see p. 150); though for practical structural reasons the double circuit is preferable in some cases. A double circuit, that is to say one resembling No. 3 or No. 8 of the accompanying Fig. 100, has in general the advantages that it affords a more stable framework, and that its magnetic field is less liable to distortion than that of No. 2. These points should be borne in mind in considering the forms depicted in the accompanying figures. No. 1 of these illustrations shows the form adopted by Wilde for use with the shuttle-wound armature of Siemens. Two slabs of iron are connected at the top by a yoke, and are bolted below to two massive pole-pieces. There are four joints in the magnetic circuit in addition to the armature gaps, and the yoke is insufficient. No. 2 shows the form adopted in the Edison dynamos (standard bipolar pattern). The upright cores are stout cylinders. The yoke is of immense thickness; the pole pieces are massive, but their lower corners are cut away. There are as many joints as in Wilde's form; but such a circuit should possess a far higher magnetic conductivity than Wilde's, owing to the greater cross section.

One difficulty with such single circuit forms is how to mount them upon a suitable bed-plate. If mounted on a bed-plate

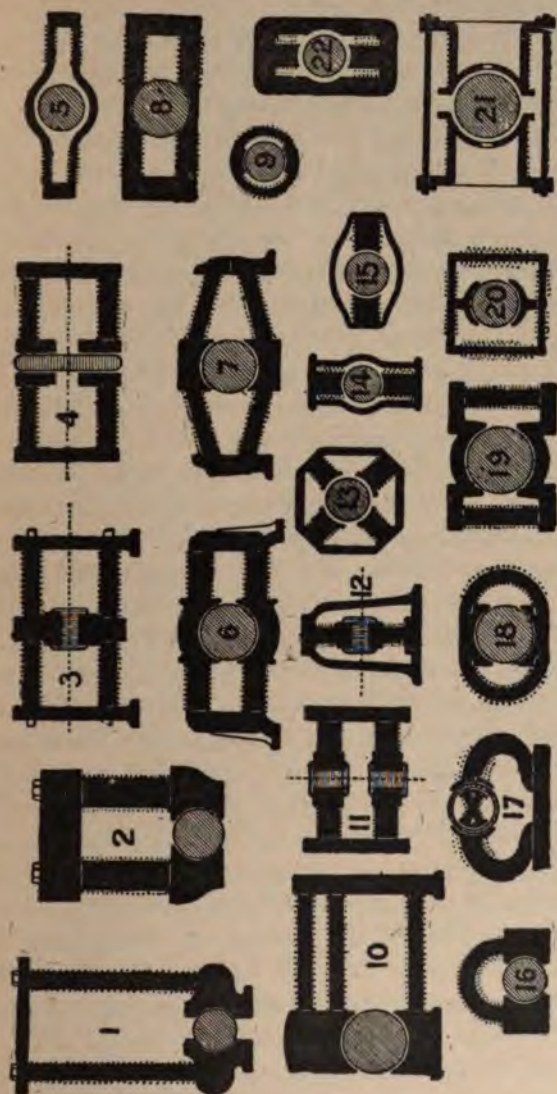


FIG. 100.—TYPICAL FORMS FIELD-MAGNETS.

of iron, considerable fraction of the magnetism will be short-circuited away from the armature, as has been shown in the

preceding chapter. In the larger form, No. 10, used at one time by Edison, this difficulty was only partially obviated by turning the magnets on one side.

A favorite type of field-magnet, having a double magnetic circuit with "consequent" poles, is represented in No. 3; it was introduced by Gramme. It may be looked upon as the combination of two such forms as No. 1, with common pole-pieces. Nos. 3 to 9 may be looked upon as modifications of a single fundamental idea. No. 4 gives the form used in the Brush dynamo (plan), the two magnetic circuits converging upon the ring armature. The diagram will serve equally for many forms of flat-ring machine; but in most of these the poles at the two flanks of the ring are joined by a common hollow pole-piece, embracing a portion of the periphery of the ring. No. 5 shows an early form of Siemens, with arched ribs of wrought iron, having consequent poles at the arch. The circuit is here of insufficient cross section. No. 6 depicts a form adopted by Weston: and very similar forms have been used by Crompton, and by Paterson and Cooper. There is a better cross-section here. No. 7 is a form used by Burgin and Crompton, and differs but slightly from the last. It has one advantage—that the number of joints in the circuit is reduced. No. 8 is a form used by Crompton, Kapp and others. No. 9 is the form adopted in the little Griscom motor. No. 18 is a further modification due to Kapp. No. 19, which also has consequent poles, was used by McTighe, by Joel, and by Hopkinson ("Manchester" dynamo), by Clark, Muirhead & Co. ("Westminster" dynamo), by C. E. L. Brown (Oerlikon), and in some of Sprague's motors; but with slight differences in proportions of the details. The main difference between No. 19 and No. 6 lies in the position selected for placing the coils, No. 19 requiring two, No. 6 four. No. 20, which is a design of Elwell and Parker, is a further modification of No. 3, and would be improved by having a greater cross-section. In No. 3 (Gramme), it is usual to cast the pole-pieces and end-plates, but to use wrought iron for the longitudinal cores. The requisite polar surface must be got by some means, and when the core was made thin, the two courses

open were either to fasten upon the core a massive pole-piece (Nos. 1, 3, 4, 6, 7, 19, 20), or else to arch the core No. 5 so that its lateral surface was available as a pole. Now, however, that it is known that massive cores are of advantage, the requisite polar surface can be obtained without adding any polar expansion or "piece," but by merely shaping the core to the requisite form (No. 8). This must not be regarded as a thinning of the magnet; for though mere reduction of cross-section at any part of the circuit would reduce the magnetic conductivity, reduction of the thickness for the purpose of bringing the armature more closely into the circuit will have quite the opposite effect. In fact the horizontal bars above and below the armature might be thinned away to nothing at their middle point, but for structural reasons. In all such forms of double magnetic circuit each half of the field-magnet may be regarded as having to furnish magnetic lines to its own half of the armature. Nos. 11 to 15 illustrate forms of field-magnet having *salient*, as distinguished from *consequent* poles. No. 11 is a double Gramme machine designed by Deprez. Nos. 12 and 13 are two of the innumerable patterns due to Gramme himself. These are both of cast iron; and it will be noticed that in No. 13 there are no joints, it being cast in one piece. No. 14 is a form used by Hochhausen, and is practically identical with 21, save in the position of the axis of rotation. The iron flanks of No. 14 tend to produce a certain short-circuiting of the magnetism by their proximity to the poles; and their sectional area is insufficient. No. 15, used by Van de Poele, is similar. No. 16 is the form used by the author in small motors, and is cast in one piece. The semicircular form adopted for the core was intended to reduce the magnetic circuit to a minimum length. No. 17 has salient poles reinforced by other electro-magnets within the armature. No. 21 shows in section the double tubular magnets of the Thomson-Houston dynamo, the spherical armature being placed, as in Nos. 12, 14 and 15, between two salient poles. There is a curious analogy between Nos. 21 and 19; but they entirely differ in the position of the coils. No. 22 is a design by Kapp, in which there are two salient poles

of similar polarity, and two consequent poles between them, one pair of coils sufficing to magnetize the whole quadruple

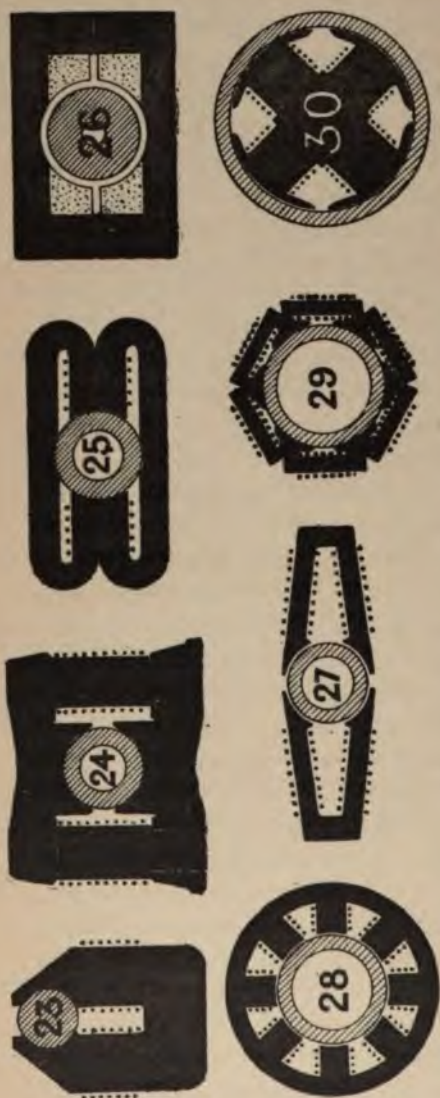


FIG. 101.—TYPICAL FORMS OF FIELD-MAGNETS.

circuit. Almost identical forms have been employed by Rankine Kennedy ("iron-clad" dynamo), No. 25. Lahmeyer and Wensström employ iron-clad forms resembling No. 15. That of Wensström has for its yoke an external iron cylinder. No. 23, Fig. 101, with armature at the top, is known as the "over-type" of bipolar machines. It is an old form which was revived in 1884 by Gramme ("type supérieur"), by Kapp, by Siemens and by others. No. 24 is Brown's very massive form. No. 26 is designed by Prof. George Forbes. The iron-work is in two halves; the coils, which are entirely enclosed, are so placed as to magnetize the armature directly, one coil occupying all the available space between the field-magnet

and the upper half of the armature; the other the similar space around the lower half. No. 27 is a 4-pole form

adopted by Elwell-Parker, and also by Crompton. No. 28 is a multipolar form, used by Wilde, Gramme and others, the poles which surround the ring being alternately of opposite sign. It is now largely used for alternate-current machines such as those of Westinghouse, Mather and Platt (Hopkinson), and others. In No. 22, a modification of this design by Thury, for use with a drum armature, the six inwardly-directed poles are magnetized by coils wound upon the external hexagonal frame. No. 30 is a sketch of a form introduced by Siemens and Halske, and also by Ganz, Fein and others, wherein an external ring rotates outside a very compact and substantial



FIGS. 102, 103.—TYPICAL FORMS OF FIELD-MAGNETS.

4-pole electro-magnet. Similar machines, but with more than four internal poles, are largely used in Germany, for large central-station machines.

Another form of field-magnet is shown in No. 31. This, which is a single horse-shoe with but one coil upon it, was a design by the author of this work early in 1886: it has been used largely by Goolden and Co., by Greenwood and Batley, and other British makers. No. 32 represents also a machine requiring but one coil, and is of the iron-clad type. It was devised by McTighe in 1882, and has been revived by Stafford and Eaves. A pattern designed by Mordey for the Brush Company resembles No. 32, but has an external iron cylinder to enclose the coil. In Fig. 96 is represented Lahmeyer's form, also with inward-pointing poles: like the preceding it belongs to the "iron-clad" type, the yoke of the magnet being exterior.

Eickemeyer's dynamo (Fig. 104) realizes the suggestion of Forbes to place the magnetizing coils over the armature. The coils, which are separately wound on formers, fit into



FIG. 104.—EICKEMEYER'S DYNAMO.

recesses between the upper and lower yokes and the inwardly projecting polar masses. Fig. 105 gives a view showing the interior disposition when one of the polar masses is removed. The defect of such forms is the difficulty of ventilating the closely enclosed armature.

A typical form for alternate-current machines is that introduced by Wilde, and used by Siemens, Ferranti and others, having two crowns of alternate poles facing one another.

Fig. 107 represents a form of 4-pole field-magnet used by the Brush Company for their Victoria (Mordey) machines, having double magnetic circuits

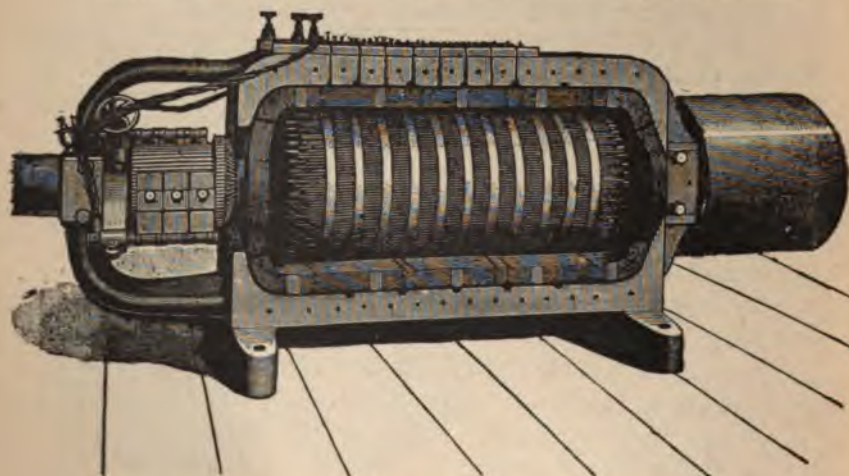


FIG. 105.—EICKEMEYER'S DYNAMO, WITH MAGNETIZING COILS SURROUNDING ARMATURE.

and consequent poles. The cores to receive the coils are of wrought iron, whilst the end frames and pole-pieces are cast.

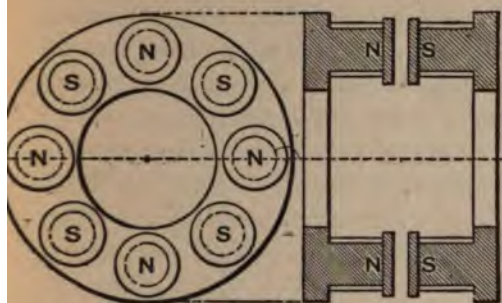


FIG. 106.—TYPICAL ALTERNATE-CURRENT FIELD-MAGNET.

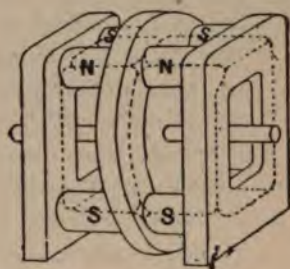


FIG. 107.—FOUR POLE MAGNET (MORDEY).

This should be contrasted with the form of 4-pole magnet, Fig. 108, designed in 1888 by Brown, and constructed by the

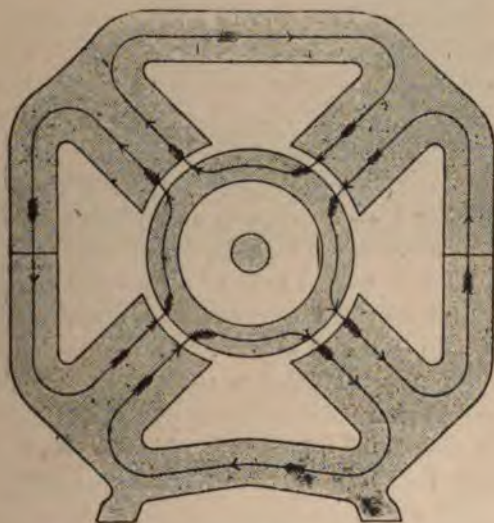


FIG. 108.—FOUR-POLE MAGNET (BROWN).

Oerlikon works, for some large 300 horse-power machines for transmission of power. These are made entirely of cast iron,

and have salient poles. The direction of the flux through these machines is indicated by dotted lines.

The most notable departure in the forms of field-magnets in recent years is that due to Mordey, in whose alternator there is a field magnet (see Fig. 419 and Plate XIV.), which, though it possesses but a single magnetic circuit with one exciting coil upon it, is nevertheless multipolar. This result is attained by the use of multiple pole-pieces which subdivide the magnetic flux into a number of separate magnetic fields. The field-magnet of the three-phase alternator (Figs. 422 and 425), designed by Brown for the transmission of power from Lauffen to Frankfort, is also of this improved kind, with a single exciting coil. In many recent machines a similar simplification is to be found.

Among such a multiplicity of designs one seeks for some indication as to the best. But the best for one purpose is not the best for all. Some designs are suitable for cast iron; others for wrought iron; others again, such as Figs. 102 and 107, are expressly intended to be composite, having wrought cores for the bobbins and cast polar masses. It is desirable, where possible, to have the core upon which the coils are wound cylindrical, as that shape has the least perimeter for a given sectional area, and in consequence allows a saving in copper wire as well as making the winding simpler. Of course cylindrical cores are not suitable for machines with long drum armatures. There is a tendency at the present time to make the wound core of a material of high permeability, so that its perimeter can be reduced and a saving effected both in iron and copper. As the exciting coils are generally wound on detachable reels, the shape of the field-magnet should permit of these being put off and on. For small machines a simple circuit is probably the best. For large machines it is found needful to multiply the number of poles: and for alternators, multipolar forms are necessary for obtaining a sufficiently frequent alternation of currents.

Probably the future will see a general simplification of multipolar forms by the adoption of branched magnetic circuits.

calculating those forms which have double or multiple

magnetic circuits, it is usual to simplify matters by considering one element of the whole, and making the calculations for it. Thus, for example, in Fig. 109, which depicts the half of such a machine as No. 8 of Fig. 100, it is sufficient to calculate the magnetic reluctances of half the machine in order to ascertain the number of ampere-turns that must be wound upon it; a similar number being wound upon the other half. Forms with a double magnetic circuit are preferable to those, such as Nos. 2, 23, and 31, with a single magnetic circuit, in all cases where there is likely to be much armature reaction. For in such form as No. 23 the field is weaker under the two

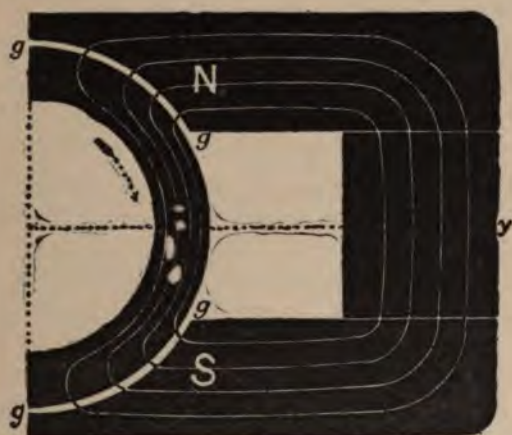


FIG. 109.—HALF OF A DOUBLE MAGNETIC CIRCUIT MACHINE.

upper pole-tips than between the two lower ends of the pole-faces: in consequence, there is a powerful attraction downward of the armature. Further, because of this inequality of field the cross-magnetizing force of the armature will produce, in the single-magnet forms, an unsymmetrical distortion. As a consequence there is sure to be sparking at the brushes. For large-load bipolar armatures it is advisable not only to use double-magnets, but to separate their two halves by a distance-piece of brass.

CHAPTER IX.

ELEMENTARY THEORY OF THE DYNAMO. MAGNETO, AND
SEPARATELY-EXCITED MACHINES. SERIES MACHINES.
SHUNT MACHINES.

EXPERIENCE has shown that the main problems that require to be considered in the design of dynamos, are best solved by reference to the *magnetic circuit of the machine as a whole*, the iron core inside the armature being regarded as a constituent part of that circuit. In all that follows the armature is regarded merely as consisting of a certain number Z of conductors, grouped in a particular way around an axis of rotation, their function being to cut across the magnetic lines that are furnished by the magnetic circuit. The symbol N stands for the *magnetic flux*, which, in the case of bipolar machines, is *the whole number of magnetic lines that traverse the armature*, entering it on one side and again leaving it on the other. For multipolar machines, N stands for the flux from one pole that traverses the armature.

The number of revolutions *per second* made by the armature is denoted by the symbol n . It is found that the average electromotive-force generated by the armature is simply proportional to each of these quantities, so that by taking the appropriate units we may write, as will presently be seen, as the fundamental equation

$$(\text{average}) E = n Z N. \quad . \quad . \quad . \quad [I.]$$

In the present chapter an expression is first found for the average electromotive-force, which expression serves as the fundamental equation of all dynamos. Then by introducing appropriate formulæ for the various circuits, equations are deduced for the various kinds of series-wound, shunt-wound and compound-wound dynamos.

SYMBOLS USED.

It may be well to point out that in this and the succeeding chapters the following symbols are used in the following significations :—

A	area, expressed in <i>square centimetres</i> .	
B	the flux-density, or number of magnetic lines per square centimetre.	
b	number of external wires in a section of the armature. In speaking of alternators <i>b</i> stands for "the breadth coefficient" (see Chap. XXIII.).	
β	angular breadth of a section of armature coil or of segment of collector.	
C	current in external circuit,	} expressed in amperes.
C_a	current in armature,	
C_m	current in series coil or main circuit,	
C_s	current in shunt coil.	
c	number of segments of collector or commutator.	} expressed in volts.
E	entire electromotive-force generated in an armature,	
<i>e</i>	difference of potential from terminal to terminal,	
$\mathcal{E}$	electromotive-force of some external supply of electricity,	
η	economic coefficient, or efficiency (see pp. 107 and 187, and Chap. XXX.)	
F	force (i. e. push or pull), expressed in either <i>dynes</i> , <i>poundals</i> , <i>grammes'</i> weight or <i>pounds'</i> weight.	
H	intensity of magnetic field (lines per sq. centim. <i>in air</i>).	
L	coefficient of self-induction.	
λ	average length of one turn of wire; also used for angle of lead.	
μ	magnetic permeability of iron.	
N	the magnetic flux, or whole number of magnetic lines that traverse a magnetic circuit.	
<i>n</i>	number of revolutions <i>per second</i> . In alternate-current problems <i>n</i> = the frequency.	
ω	angular velocity (expressed in <i>radians-per-second</i>).	
<i>p</i>	number of <i>pairs</i> of poles. In alternate-current problems the symbol <i>p</i> is used for the <i>pulsation</i> , $p = 2\pi n$.	
R	resistance of external circuit,	} expressed in ohms.
r_a	resistance of armature coils,	
r_s	resistance of shunt coils,	
r_m	resistance of series coil on field-magnets,	
r	internal resistance of dynamo; equal to $r_a + r_m$ or to $r_a + r_s$ according to circumstances,	
ρ	resistance per unit of length,	
S	number of spirals or turns of wire in coil.	

- S_m number of turns in a coil in the main circuit, in series with armature.
 S_s number of turns in a coil in shunt.
 T torque, or turning moment, or angular force, or couple, expressed in *dyne-centimetres*, *gramme-centimetres*, *metre-kilogrammes*, or *pound-feet*, according to circumstances.
 T is also used in the section on alternate currents for the periodic time of the alternating current, measured in *seconds*.
 t time measured in *seconds*.
 v coefficient of allowance for magnetic leakage.
 V volts at terminals of dynamo or motor.
 W } activity, or power, or work-per-second, expressed in *watts* or in
 w } *horse-power*.
 Z number of conductors on armature, counted all round the periphery.
 ϕ angle of phase difference between alternating currents or electromotive-forces.

Wherever inch units are used instead of centimetre units, the marks used on p. 104 will be employed for distinction.

FUNDAMENTAL EQUATION OF DYNAMO.

To find the average electromotive-force of a moving conductor, we must remember that, by definition, see p. 22, this is (in absolute C.G.S. units) numerically equal to the number of magnetic lines that are cut in one second by the conductor. Also the practical unit, the *volt* being by definition equal to 10^8 absolute C.G.S. units of electromotive-force; it will be necessary to divide the number of C.G.S. units by 10^8 in order to reduce the number to volts. Further, when there are, as in the armatures of dynamos, a number of conductors in series with one another, the total electromotive-force of the dynamo will be equal to the sum of the electromotive-forces of those conductors that are in series with one another. The fundamental equation will then be written :

$$(\text{average}) E \text{ (in volts)} = n Z N \div 10^8 [Ia.]$$

We will deal first with an ordinary two-pole dynamo, having an armature in which the number of "sections" is denominated by the symbol c ; the number of "segments"

the symbol ω represent the angular velocity. Then $\omega = 2\pi n$; for, in each revolution, the angle described is 2π radians or 360 degrees. Consequently $n = \omega/2\pi$, which gives;

$$(\text{Average}) E = \frac{\omega}{2\pi} Z N \dots \dots \dots [\text{Ib.}]$$

It will be observed that this electromotive-force is simply an average; and it depends on the construction of the armature how much fluctuation there is in the value during a rotation.

If, as in Fig. 110, the armature had but two external conductors forming a simple loop, then the electromotive-force would fluctuate between zero and a maximum. Calling the

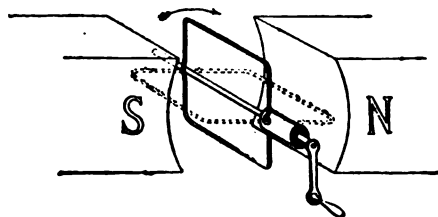


FIG. 110.—IDEAL SIMPLE DYNAMO.

lowest point of the rotating loop in its vertical position 0° , then the position on the left of the dotted line will be 90° , if we reckon the rotation in the clockwise direction. The top point will be 180° , and the point on the

extreme right 270° . Then the induced electromotive-force will be zero as the coil passes through 0° and 180° (for at the positions 0° and 180° the conductors will be sliding along rather than cutting, the magnetic lines), and a maximum as the coil passes through 90° and 270° . The rate of enclosing or "cutting" will be a maximum when the actual number of lines enclosed is a minimum, and *vice versa*. (See p. 31.)

At any intermediate angle, if the field is uniform, the actual number of lines of force enclosed is proportional to the cosine of the angle through which the coil has turned from its zero position, and the electromotive-force will be proportional to the sine of that angle. Strictly speaking, we ought to take the sine with a negative value to represent the electromotive-force, because as usually defined the induced electromotive-force is proportional to the rate of decrease in the number of

into positive ones; the brushes being so arranged as to slide from one part of the commutator to the other at the moment when the inverse induction begins. This gives the curve the form of Fig 112, which therefore represents how the voltage pulsates in the circuit of a simple old-fashioned shuttle-wound Siemens armature. Now if we could level these hills, and

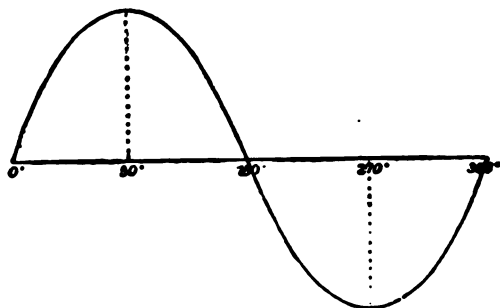


FIG. 111.

change our undulating induction into a steady one, we should get a single straight line, shown in Fig. 112 as a dotted line enclosing below it a rectangular area equal to the sum of the areas enclosed by the sinuous curves, and therefore at a height which is the average of the heights of all the points along the curves: in fact, since each sinuous curve is part of a

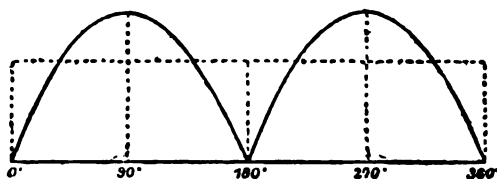


FIG. 112.

curve of sines, the *average* height will be $2/\pi$, or about $\frac{2}{3}$ of the maximum height. In consequence of self-induction in the coils, the current will not actually fluctuate¹ as much as the voltage, the hollows being partly filled.

¹ See remarks by Cromwell F. Varley in *Phil. Mag.*, 1867, and by Puluj in *Sitzungsber. Wien. Akad.*, IIa, May 1891.

Fluctuations in a Closed-coiled Armature.—As shown on pp. 39 and 60, it is, for reasons of construction, usual to wind armature coils in two sets connected in parallel. If each of the two coils consisted of 100 turns, their joint effect in inducing electromotive-force would be no greater than that of either of them separately, but the internal resistance of the armature would be halved. From this point onwards in the argument it will be assumed that the armature windings consist of *pairs* of coils. Thus, instead of one coil of 200 turns, as shown in Fig. 113, we shall take it that there is a pair of coils each of 100 turns, as in Fig. 114.

Now suppose that, in order to get a less fluctuating effect, we divide each of our original single pair of coils into two parts, and set these at right angles to one another. To take



FIG. 113.



FIG. 114.

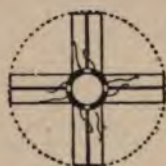


FIG. 115.

a numerical case, suppose there were originally 100 turns in each coil, and we split each into two coils of fifty turns, but set them across one another so that one comes into the best position in the field as the other is going out of it. (This arrangement is indicated in Fig. 115, which may be contrasted with Fig. 114.) In this case we shall have two sets of overlapping curves—each of them will have to be put half as high as before, because the equivalent area of each coil is only half what it was for the whole coil. Then, if there were no commutator, the induced electromotive-force in the two sets of coils would fluctuate as shown by the two curves of Fig. 116, which differ by a quarter-period from one another. But if the ends of the two “sections” of the coil are joined to a proper commutator, all the “inverse” inductions will be commuted into “direct” ones, and the two curves would

then become as in Fig. 117. The next process is to ascertain what the joint result of these overlapping electromotive-forces will be : it is evident that from 0° and 90° the two inductive actions are assisting one another, and that at 45° they are

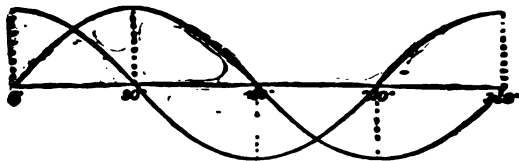


FIG. 116.

equal. The nett result here is therefore double either of them ; and, in fact, the curve representing the *sum* of the two curves is given in Fig. 118. This curve shows at once a step towards *continuity*, as the fluctuations are far less than those of the

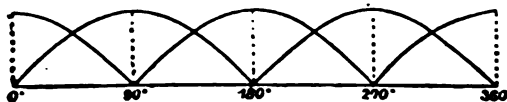


FIG. 117.

single coil, Fig. 112. If, as before, we level the undulating tops by a dotted line, we get precisely the same height as before. The *total* amount of induction (the total cutting of lines per second) is the same, and the *average* electromotive-

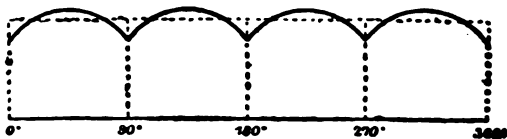


FIG. 118.

force is the same. There is no gain, then, in the total electric work resulting from rearranging the armature coils in two sets at right angles to each other ; but there is a real gain in the greater continuity and smoothness of the current.

If we again split our coils and arrange them as shown in Fig. 119 at angles of 45° , in four sets of pairs of coils of twenty-five turns each, and connect them up to a proper commutator, we shall get an effect which is very easily represented by constructing two curves, each similar to the last but each of half the height, and compounding them together (Fig. 120). One of them will of course have the maximum heights of crests occurring 45° further along than those of the other curve; and when these are compounded together we get for a resultant a curve shown in Fig. 121, which has exactly the same average height as before, but which has still less of fluctuation. It is easily conceived that this process of dividing the coil into sections, and spacing these sections out at equal angles symmetrically, would give us a result approaching as near as we choose to an absolutely continuous



FIG. 119.

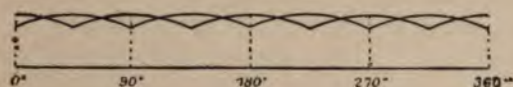


FIG. 120.

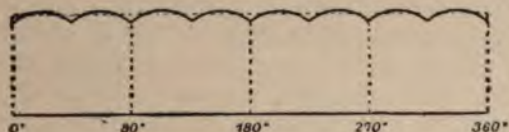


FIG. 121.

one. If our original pair of coils of 100 turns each were split into twenty sets of pairs of five turns each, or even into ten sets of pairs of ten turns each, the approach to continuity would be very nearly truly attained.

Calculation of Fluctuations.—If the variations of the electromotive-force literally followed a sine law, it would not be difficult to calculate the amount of fluctuation when a commutator with any particular number of segments is used. Some calculations on this basis given in previous editions showed that with a 20-

part commutator the fluctuations were less than 1 per cent. of the whole, and with a 36-part commutator they were less than $\frac{1}{4}$ of 1 per cent. But as a matter of fact the distribution of the field in the part where coils are commuted does not obey any such law; and in the absence of information as to the exact way in which the induction of electromotive-force varies in the fringe of the field, such calculations may be very wide of the mark. It suffices to know that a 20-part commutator in a bipolar field gives fluctuations that are practically negligible, so that if it were not for other considerations—such as avoidance of sparking—it would be a useless refinement to employ commutators having more numerous segments.

Measurement of Fluctuation.—The relative amount of fluctuation in the current furnished by a dynamo may be observed by noticing the inductive effect on a neighbouring circuit into which is introduced a Bell telephone receiver. If the current is steady there will be no sound heard. If it fluctuate, each fluctuation will induce a corresponding secondary current in the telephone circuit, and the amount and frequency of the fluctuations may be estimated by the loudness and pitch of the sound in the telephone. The fluctuations in the current of a Brush arc-light dynamo are in this manner readily detected.

Effect of Non-simultaneous Commutation.—If the brushes are not so set that the sliding of contact under one brush is not accomplished at the same instant as that under the other brush, then it is clear that there will be slightly unequal electromotive-forces in the two halves of the armature circuit. This momentary inequality will die out, to be succeeded by another inequality (of opposite sign) when commutation occurs at the other brush. The effect will be the same as though a small alternating current having $2n$ c periods of alternation per second were made to act around the circuit of the armature. Such effects may be occasioned in armatures by various causes; if the number of sections in an armature be an odd number; if the number of conductors in all the sections are not alike or their connections are unsymmetrical; or, lastly, if the contact-edges of the brushes do not lie exactly at opposite ends of a diameter.

Measurement of the Flux N.—An important problem is how to measure the actual number of magnetic lines that pass through the armature. This number is really best ascertained by calculation from the performance of the machine itself. The speed being observed by aid of a suitable speed-counter, the number of conductors round the armature being known, and the whole

electromotive-force generated in the machine being measured by proper electrical methods, then it only remains to apply the fundamental formula, transformed so as to calculate back to N :—

$$N = 10^8 \times E \div n Z.$$

To measure E while the machine is running, it must either be run upon known resistances (so as to enable E to be calculated from Ohm's law); or E may be calculated by measuring (see p. 181) the difference of potentials at the brushes with a voltmeter, and then calculating from the resistance of and current in the armature the volts lost internally, which, added to the measured volts, make up the whole E .

THE MAGNETO-MACHINE AND THE SEPARATELY- EXCITED MACHINE.

In magneto dynamos, in which the field is due to permanent magnets of steel, N depends both on the magnetism of the steel and on the iron core of the armature. The number of lines that find their way through the armature is, however, lessened by the reaction of the armature when a large current is being drawn from the machine. If the magnetism of the field-magnets were so overpoweringly great, as compared with that due to the armature coils, that this reaction was insignificantly small, then, since our fundamental formula is :

$$E = n Z N,$$

E would, for any given magneto machine, be directly proportional to n , the speed of rotation. But we know in practice that this is not the case. The number of turns by which the speed, at any output, exceeds the number that would be needed for strict proportion is called the *dead turns*. Suppose we turn a magneto machine at 600 revolutions per minute ($n = 10$, for then there will be 10 revolutions per second) and get, say, 17 volts of electromotive-force from it, then, if there were no reactions from the armature, turning it at 1200 revolutions per minute ought to give exactly 34 volts. This is never quite attained ; though in many machines the

direct proportion very nearly holds good, so long as no current is drawn from the machine to give rise to demagnetizing effects. In that case the only reaction that would cause departure from proportionality is that possibly due to eddy-currents. If the speed and the total volts generated in the armature are observed, and plotted out against one another, the straightness of the "curve"—which ought to be a straight line sloping down to the origin—will show how nearly the theoretical condition is attained.

If the current in the armature is kept constant by increasing the resistances of the circuit in proportion to the speed, the demagnetizing action of the armature can be kept constant, even though the machine is giving out a current.

In some experiments¹ made by M. Joubert at different speeds, the electromotive-force was measured by an electrometer which allowed no current whatever to pass, and the theoretical law was almost exactly fulfilled. The observations are given below.

Speed	500	720	1070	revolutions per minute.
Electromotive-force ..	108	145	208	volts.

Potential at Terminals of a Dynamo. Lost Volts.—The potential at terminals of the magneto machine—and indeed of every dynamo—is, when the machine is doing any work, less than E , the total induced electromotive-force, because part of E is employed in driving the current through the resistance of the armature. The symbol e may be conveniently used for the difference of potential between terminals. Only when the external circuit is open, so that no current whatever is generated, $e = E$. It is convenient to have an expression for e in terms of the other quantities, seeing that when any current is being generated it is impossible to measure E directly by a voltmeter or by an electrometer, whereas e can always be so measured.

Let r_a be the internal resistance of the machine, that is to say the resistance of the armature coils, and of everything else in circuit between the terminals; and let R be the

¹ See also experiments by Mordey, *Journal I. E. E.*, xix. 233, 1890.

resistance of the external circuit. Then, by Ohm's law, if C be the current,

$$E = C (r_a + R).$$

But by Ohm's law also, if e be the difference of potential between the terminals of the part of the circuit whose resistance is R ,

$$e = C R;$$

whence

$$\frac{e}{E} = \frac{R}{r_a + R}; \quad \dots \dots \dots \text{[III.]}$$

also

$$e = \frac{R}{r_a + R} E.$$

It is also convenient to note that

$$E = \frac{r_a + R}{R} e;$$

for this formula enables us to calculate the value of E from observations of e made with a voltmeter. But often the values of R are unknown: hence the following is more useful. By subtracting the second of the above equations from the first of them we get:—

$$E - e = C r_a,$$

or

$$e = E - C r_a \quad \dots \dots \dots \text{[IV.]}$$

This is equivalent to saying that the volts at the terminals are equal to the whole volts generated in the armature less the volts needed to drive the current C through the internal resistance r . The volts $C r_a$, which are thus not available in the external circuit, are called the *lost volts*: they will be less the smaller the internal resistance is. If e is observed by applying a voltmeter, then E can be found by adding to it the lost volts; and these can be calculated by measuring with an amperemeter the current flowing through the armature and multiplying this by the known internal resistance. In good modern dynamos the lost volts at full load do not amount to more than 2 or 3 per cent. of the whole voltage.

Relation between whole Electromotive-force and Difference of Potentials at the Terminals.—The essential distinction pointed out above between the whole electromotive-force E , and that part of it which is available as a difference of potentials at the terminals e , may be further illustrated by the following¹ geometrical demonstration.

In a machine (such as are chiefly dealt with later) in which e is constant, E will not be constant, except in the unattainable case of a machine which has no internal resistance. Let r represent the internal resistance of the machine, including that of the armature and of any magnet coils that are in the main circuit ($r = r_a + r_m$); then,

$$E = CR + Cr = e + Cr.$$

If E is constant, then e cannot be constant when C varies; and if e is constant, E cannot be. We have then two cases to consider:—

(1) E constant.—Take resistances as abscissæ and electromotive-forces as ordinates, and plot out (Fig. 122) $OA = r$, $AN = R$, $OB = E$. The line BN represents the fall of potential through the entire circuit. Of the whole electromotive-force OB , a part equal to CM is expended in driving

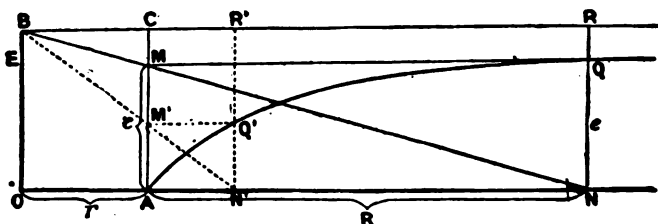


FIG. 122.

the current through the resistances r , leaving the part AM available as the difference of potential at the terminals, when the total resistance of the circuit is represented by the length from O to N . Accordingly, at N erect a vertical line NQ equal to AM . Take a less external resistance $R' = AN'$ and by a similar process we find that the corresponding value

¹ *Elektrotechnische Zeitschrift*, iv. 161, April, 1883.

of e is $A M'$ or $N' Q'$. Similarly, any number of points may be determined; they will all lie on the curve $A Q Q'$, which therefore shows how, as the external resistance is increased the terminal potential rises, whilst the whole electromotive force remains constant and is represented by the horizontal line $B R$. The equation of this curve is given by the condition

$$\frac{E-e}{E} = \frac{r}{R+r},$$

whence $(E-e)(R+r) = E r = \text{constant}$; which equation is the equation of an equilateral hyperbola having $O B$ and $B R$ as asymptotes.

(2) e constant.—As in the preceding case, $O A = r$; $A N = B$; and $A M = e$. From N (Fig. 123) draw the line

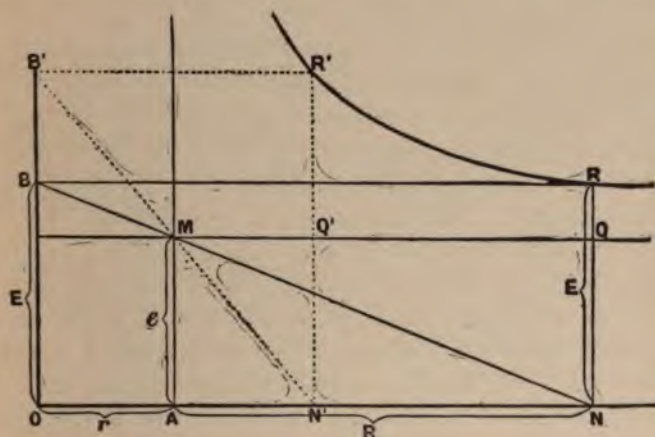


FIG. 123.

$N M$ and produce it backwards to B . Then $O B$ represents that value of E which will give e volts at terminals when $R = N M$. Accordingly set off at N the line $N R = O B$. In a precisely similar way draw $N' B'$, to correspond with any other value of R , and make $N' R'$ equal to $O B'$. $N' R'$ represents the value of E when the value of the external resistance R is equal to $A N'$. By determining other values we obtain

the successive points of the curve RR' , which shows how the whole electromotive-force must vary in order to maintain a constant difference of potentials at the terminals, as represented by the horizontal line MQ . The equation to this curve (also an equilateral hyperbola) is given by the condition

$$\frac{E - e}{r} = \frac{e}{R}$$

or

$$(E - e) R = e r = \text{constant.}$$

The Separately-excited Dynamo.—For separately-excited dynamos the same formulæ hold good as for magneto dynamos; but in this case N depends upon the strength of the independent exciting current.

In estimating the nett (or commercial) efficiency of a separately-excited dynamo, the energy spent per second in exciting the field magnets ought to be taken into account.

Characteristic of Magneto Machine, and of Separately-excited Dynamo.—In the magneto dynamo the magnetism of the steel magnets is approximately constant. So is the magnetism in the iron of separately-excited machines if the exciting current is kept constant. This has given rise to a common idea that in such machines the electromotive-force depends on the speed alone. This is not true. For owing to the cross-magnetizing and demagnetizing tendency of the currents in the armature coils, the number of magnetic lines that actually traverses the armature core diminishes when the currents in the armature are strong. The stronger the current in the armature the stronger the reaction. And, as explained on p. 84, the demagnetizing tendency increases with the lead given to the brushes. As will be explained (p. 196), it is convenient to plot out certain curves, known as *characteristics*, to exhibit the relation that subsists between the electromotive-force and the current under different conditions of speed, resistance, &c. Usually one of the conditions assumed is that the speed is constant. Such curves are particularly useful for studying the various reactions that exist between the field-magnet and armature.

A careful study of the characteristics of separately-excited dynamos was made by Mr. W. B. Esson,¹ who gave the following curve for a separately-excited dynamo having a modified Pacinotti ring armature. The line *E* (Fig. 124) represents the total electromotive-force if there were no reactions. The line *e* represents the values of the potential between the brushes of the machine as it would be if there were no reaction.

The curved line *B* gives the actually-observed values of *e* when different currents were taken from the machine. The greater drop at the lower end of the curve is probably due to the greater demagnetizing effect when there is a considerable lead at the brushes. The characteristic always shows such downward curvature more when the field-magnets are weakly excited.

Efficiency and Economic Coefficient of Dynamos.—

Suppose that we know the actual mechanical horse-power applied in driving a dynamo. This can be measured directly either by using a transmission dynamometer, or by taking an indicator diagram

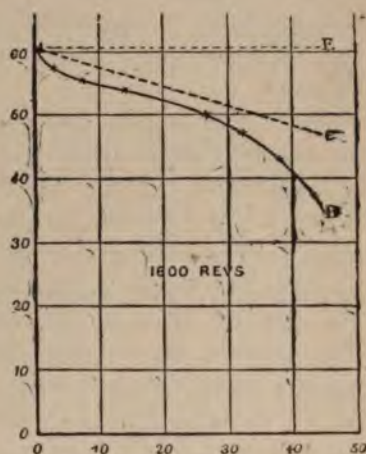


FIG. 124.—CHARACTERISTIC OF SEPARATELY-EXCITED DYNAMO.

from the steam engine that is driving it, or, in certain special cases where the field-magnets can be pivoted or counterpoised, by applying the method originally pursued by the Rev. F. J. Smith, and later described by M. Marcel Deprez and by Professor Brackett, in which the actual mechanical interaction between the armature and field-magnets is utilized to measure the horse-power used in driving the machine. If, then, we know the mechanical horse-power applied, and if

¹*Electrical Review*. xiv. 393, April 1884. See also papers by M. Marcel Deprez, *Comptes Rendus*, xciv. pp. 15 and 86, 1882.

we measure the output of electric horse-power of the dynamo, we have by comparing the mechanical power absorbed with the electric power developed, a measure of the *efficiency* of the dynamo. It must, of course, be borne in mind that part of the electric energy developed is inevitably wasted in the machine itself, in consequence of the resistance in the wire of the armature, and, in the case of self-excited dynamos, in the wire of the field-magnet coils. There must, therefore, be drawn the distinction mentioned on p. 107 between the gross efficiency of the machine, or as it is sometimes called, its "efficiency of electric conversion," and its nett efficiency or commercial efficiency. We must, however, have the means of measuring the electric output of the dynamo.

As is well known, the energy per second of a current is expressed as the product of two factors, namely, the number of *amperes* of current, and the number of *volts* of potential between the two ends of that part of circuit in which the energy to be measured is being expended. The number of amperes of current is measured by a suitable amperemeter; the number of volts of potential by a suitable voltmeter. The product of the volts into the amperes expresses the electric energy expended per second, in terms of the unit of power denominated the *watt* (1000 watts = 1 *kilowatt*). As 1 horse-power is equal to 746 watts, the number of volt-amperes (*i. e.* of watts) must be divided by 746 to give the result in horse-power. If C represents the current in amperes, and e the difference of potential in volts, then the number of watts of power, for which we may use the symbol w , may be written

$$w = e C \div 746. \quad . \quad . \quad . \quad . \quad . \quad [V.]$$

The ratio of the useful electrical power realized in the external circuit to the total electric power that is developed in the armature is called the "electrical efficiency" or "economic coefficient" of the machine. It may be expressed algebraically as follows:—If through an armature there is

flowing a current of C amperes, and its total electromotive-force be E volts, then its total electric activity will be

$$= E C_a \text{ (watts).}$$

If the volts of pressure between the terminals of the dynamo be e , then the useful activity is

$$= e C \text{ watts.}$$

Using the symbol η for the "economic coefficient," or so-called "electrical efficiency," we have

$$\eta = \frac{\text{useful activity}}{\text{total activity}} = \frac{e C}{E C_a},$$

or, if the machine has no shunt, so that C and C_a are the same thing,

$$\eta = \frac{e}{E}.$$

But we know that the ratio $\frac{e}{E}$ depends on the relation of the internal and external resistances, for

$$\frac{e}{E} = \frac{R}{r + R} \text{ (see equation [III.])},$$

where R is the resistance of the external circuit, and r the internal resistance (armature, magnets, etc.) of the machine. Hence, for a series dynamo or a magneto machine,

$$\eta = \frac{R}{r + R} \cdot \cdot \cdot \cdot \cdot \cdot \cdot \text{ [VI.]}$$

Obviously, this coefficient will approach more and more nearly to *unity* the more that the value of r can be diminished. For if a machine could be constructed of *no* internal resistance there would be none of the energy of the current expended in driving the current through the armature and wasted in heating its coils.

We shall see later on how the expression for the economic

coefficient η must be modified in the case of shunt dynamos and compound dynamos.

Remembering that the gross electric power of the machine is $E C_a$ watts, or, in horse-power $E C_a \div 746$, we have for the *gross efficiency*, or efficiency of electric conversion,

$$\frac{E C_a}{H. P. \times 746'}$$

and for the *nett efficiency*, or useful commercial efficiency.

$$\frac{e C}{H. P. \times 746'}$$

It will be seen that, as the first of these expressions contains E , and the second e , the net efficiency can be obtained from the gross efficiency by multiplying by η , the economic coefficient.

Variation of Economic Coefficient with Current.—It must be noticed before passing from this topic that since C , the current, enters into each of the expressions for efficiency as a factor, and as C depends not only on the resistance of the machine itself, but on that of the lamps, or other parts of the system which it is used to feed, the efficiency of the dynamo will differ at different loads. As a rule the efficiency of a dynamo is greater at low loads than at full load, owing to the circumstance that the heat-waste increases as the square of the current. This should be contrasted with the case of steam engines in which the efficiency is highest at full load.

THE SERIES DYNAMO.

In the series dynamo (see Fig. 125, also Fig. 39), there is but one circuit, and therefore but one current, whose strength C depends on the electromotive-force E and on the sum of resistances in the circuit. These are:—

R = the external (variable) resistance.

r_a = the resistance of the armature.

r_m = the resistance of the field-magnet coils.

By Ohm's law—

$$E = (R + r_a + r_m) C.$$

Also e , the difference of potential between the terminals of the machine, is

$$e = C R.$$

It is also convenient to find an expression for the difference of potential between the brushes of the machine; the volts measured here being greater than e , because of the resistance of the field-magnets; and less than E , because of the resistance of the armature coils. For this difference of potential between brushes we will use the symbol ϵ . Then, by Ohm's law, remembering that the current running through r_m and R is of strength C , we have

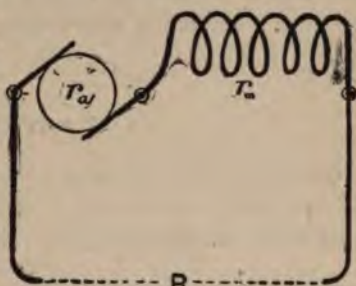


FIG. 125.

$$\epsilon = (R + r_m) C = E - r_a C;$$

whence, also,

$$e = E - (r_a + r_m) C.$$

Economic Coefficient of Series Dynamo.—From Joule's law of energy of current it follows that the economic coefficient η , which is the ratio of the useful electric energy available in the external circuit to the total electric energy developed, will be

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{C^2 R t}{C^2 (R + r_a + r_m) t} = \frac{e}{E},$$

or

$$\eta = \frac{R}{R + r_a + r_m} \quad \dots \dots \dots \text{[VII.]}$$

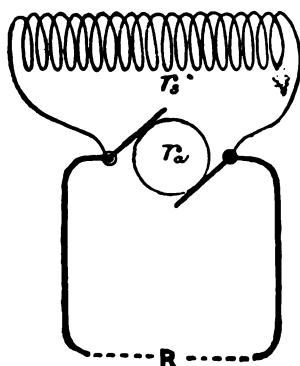
This is obviously a maximum when r_a and r_m are both very small. They are usually about equal.

Example.—In a Phoenix arc-lighting dynamo, designed by Esson, $r_a = 3.448$ ohms, and $r_m = 4.541$ ohms. If $C = 10$ amperes, the lost volts will be 79.89.

Further than this we cannot go without introducing some kind of an expression to connect E with the number of ampere-turns in the exciting coils. If we introduce the convenient approximate formula of Frölich, as given on p. 143, we shall obtain some approximate dynamo formulæ. These were given in detail on pp. 401 to 410 of the third edition of this book; wherein also, at pp. 620, 627 and 632, were given the more elaborate developments by Frölich, by Clausius, and by Rücker.

THE SHUNT DYNAMO.

In the shunt dynamo, there are two circuits to be considered; the main circuit, and the shunt circuit. The symbols used have the following meanings.



P = resistance of external main circuit (leads, lamps, &c.).

r_a = resistance of armature.

r_s = resistance of the shunt circuit (magnet coils).

C = the current in the external main circuit.

C_a = the current in the armature.

C_s = the current in the shunt circuit (the lost amperes).

Then, clearly,

$$C_a = C + C_s;$$

FIG. 126.

because the current generated in the armature splits into these two parts in the main and shunt circuits, and is equal to their sum.

We may call that part of the whole current which returns through the shunt, and is not available in the external circuit, the *lost amperes*: in a good modern machine they are at most

only 2 or 3 per cent. of the whole output of current. If e is the volts at the terminals, the lost amperes may be calculated as

$$C_s = e \div r_s.$$

For example, in the Kapp dynamo (Fig. 259), giving 200 amperes at a pressure of 105 volts at terminals, r_s was 31 ohms, hence the lost amperes were 3.4 and total current in armature at full load 203.4 amperes.

Also, by Ohm's law, we have for e the electromotive-force between terminals,

$$e = C R,$$

and also

$$e = C_s r_s;$$

because the terminals for the main circuit are also the terminals for the shunt circuit.

Further, since the nett resistance of a branched circuit is the reciprocal of the sum of the reciprocals of the resistances of its parts, the nett external resistance from terminal to terminal is equal to $\frac{R r_s}{R + r_s}$; and hence it follows that

$$E = \left(r_a + \frac{R r_s}{R + r_s} \right) C_a.$$

We may at the same time find an expression for that part of the whole electromotive-force which is being employed solely to overcome the resistance of the armature, and which is, of course, the difference between E the total electromotive-force, and e the effective electromotive-force between terminals.

Ohm's law at once gives us

$$E - e = r_a C_a,$$

or

$$E - e = r_a (C + C_s).$$

From this we also get

$$e = E - r_a (C + C_s). \quad \dots \quad [\text{VIII.}]$$

We will also find an expression for E in terms of e , and the various resistances. Taking as above

$$E = \left(\frac{R r_s}{R + r_s} + r_a \right) C_a,$$

and writing for C_a its value as $C + C_a$ and for these e/R and e/r_s respectively, we get

$$E = e \left\{ \frac{R r_s + R r_a + r_a r_s}{R + r_s} \times \frac{R + r_s}{R r_s} \right\},$$

or

$$E = e \times r_s \left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s} \right) \text{[VIII. bis.]}$$

It may be noted that the expression $\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s} \right)$ is the sum of three conductances of three paths, and is therefore equal to the conductance of these three paths united in parallel with one another; that is to say, the conductance as measured from brush to brush with the external circuit and shunt circuit joined up. Or, if we write R for the resistance of the whole system of machine and circuit, as thus measured from brush to brush, then the equation may be written

$$E = e \times r_s / R.$$

The economic coefficient η , is the ratio of the useful electric energy available in the external circuit to the total electric energy developed.

By Joule's law there is developed in t seconds in the external circuit

$$\text{useful work} = C^2 R t,$$

and in the same time there is wasted on heating,

$$\text{energy spent in shunt} = C_s^2 r_s t,$$

and

$$\text{energy wasted in armature} = C_a^2 r_a t;$$

whence

$$\frac{\text{useful work}}{\text{total work}} = \frac{C^2 R}{C^2 R + C_s^2 r_s + C_a^2 r_a} \\ = \frac{1}{1 + \frac{R}{r_s} + \frac{C^2 r_a + 2 C C_s r_a + C_s^2 r_a}{C^2 R}}$$

Eliminating the values of currents this reduces to the form,

$$\eta = \frac{1}{1 + \frac{R}{r_s} \left(1 + \frac{r_a}{r_s}\right) + \frac{r_a}{R} + 2 \frac{r_a}{r_s}}$$

Now, for brevity, write for the total internal resistance, $r_a + r_s$, the single symbol r —

$$\eta = \frac{1}{1 + \frac{Rr}{r_s r_s} + \frac{r_a}{R} + 2 \frac{r_a}{r_s}}$$

For this ratio to be a maximum it is clear that,

$$\frac{d \left(1 + \frac{R}{r_s} \cdot \frac{r}{r_s} + \frac{r_a}{R} + 2 \frac{r_a}{r_s} \right)}{dR} \text{ must} = 0,$$

or

$$\frac{r}{r_s^2} - \frac{r_a}{R^2} = 0;$$

whence

$$R^2 = \frac{r_a r_s^2}{r} = r_a r_s \frac{r_s}{r},$$

or

$$R = \sqrt{r_a r_s} \sqrt{\frac{r_s}{r}}, \quad \dots \dots \dots [\text{IX.}]$$

$$R = r_s \sqrt{\frac{r_a}{r}}, \quad \dots \dots \dots [\text{IXa.}]$$

This equation determines what particular resistance of the external main circuit will give the best economy with given internal resistances. Now substitute this value in those terms of the equation for η which contain R , and we get as their values:—

$$\frac{Rr}{r_s^2} = \frac{r}{r_s} \sqrt{\frac{r_a}{r}} = \frac{\sqrt{r_a r}}{r_s},$$

$$\frac{r_a}{R} = \frac{r_a}{r_s} \sqrt{\frac{r}{r_a}} = \frac{\sqrt{r_a r}}{r_s};$$

whence

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{1}{1 + 2 \frac{\sqrt{r_a r}}{r_s} + 2 \frac{r_a}{r_s}}.$$

This may be still further simplified, for we know that the resistance of the shunt is very high compared with that of the armature, possibly from 300 to 3000 times as great. If, then, $\frac{r_a}{r_s}$ is so small a term in comparison with the other term as to be negligible, we get

$$\eta = \frac{1}{1 + 2 \frac{\sqrt{r_a r_s}}{r_s}}; \quad [X.]$$

and since r_a is small compared with r_s , r is very nearly equal to r_s , so that we may write, as an approximate equality,

$$\eta \doteq \frac{1}{1 + 2 \frac{\sqrt{r_a r_s}}{r_s}};$$

or

$$\eta \doteq \frac{1}{1 + 2 \sqrt{\frac{r_a}{r_s}}}. \quad [XI.]$$

This latter approximate value is identical with that given by Lord Kelvin in the Report of the British Association for 1881: the equation No. [X]. is, however, more correct. It follows from equation [XI.] that the resistance of the shunt coil should be at least 324 times as great as the internal resistance of the armature, otherwise the efficiency will be lower than 90 per cent.

It may be pointed out that it follows from equation No. [IX.] above, that when the resistance of the armature is small compared with that of the shunt, so that r_a may be taken as equal to the value of r (which would be highly desirable if it could be attained in practice), then we should have

$$R = \sqrt{r_a r_s}; \quad [XII.]$$

that is to say, when the proportion between r_a and r_s is made as favorable as possible, then the best external resistance to work with from the economic point of view is that resistance which is a geometric mean between the resistances of the armature and of the shunt coils, and any departure from this will diminish the value of the economic coefficient.

In the case of machines for which an electrical efficiency not exceeding 90 per cent. is sufficient, the rule works out as follows:—Ascertain what number of lamps will be the usual full load: reckon the resistance of them when connected to the mains. Let the armature resistance be only one-twentieth of this; and let the shunt resistance be twenty times as great as this. In this case about 4 per cent. will be wasted in the armature, and about 4 per cent. in the shunt, leaving a margin of a little over 90 per cent. for the economic coefficient.

In a shunt machine described by Sir C. W. Siemens in the *Philosophical Transactions*, 1880, the results were:—

—	Armature.	Shunt Magnet.	r_s / r_a	η observed per cent.
Siemens	0·204	11·26	48·4	69·0

The Edison-Hopkinson machine, described on p. 353, gave:—

Resistance } when cold }	0·009947	16·93	1702	93·66
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The Kapp dynamo alluded to above, p. 191, and described on p. 357, gave, including the series coil with the armature:—

(Cold)	0·0306	29·133	952	92
(Warm)	0·0329	31·08	945	

CHAPTER X.

CHARACTERISTIC CURVES.

So many practical problems in the construction of dynamo-electric machines are in the present state of science solved by the use of graphic diagrams, and particularly by the use of certain curves technically called *characteristics*, that the method of constructing and using them forms an important part of the theory of the dynamo. For many practical purposes no other method is half so useful.

The characteristic curve stands indeed to the dynamo in a relation very similar to that in which the indicator diagram stands to the steam engine. As the mechanical engineer, by looking at the indicator diagram of a steam engine, can at once form an idea of the qualities of the engine, so the electrical engineer, by looking at the characteristic of the dynamo can judge of the qualities and performance of the dynamo. The comparison may even be said to reach farther than this.

The steam-engine indicator diagram serves two purposes which, though not unconnected with one another, are yet distinct. When the scale on which the diagram is drawn is known, it gives direct information as to the horse-power at which the engine is working, depending on the total area enclosed by the curve, and quite irrespective of its form. But even though the actual scale be not known, the details of the form of the curve at its various points give very definite information to the engineer as to the working of the engine, the perfection of the exhaust, the setting of the valves, the efficiency of the cut-off, and the adequacy of the supply pipes and port-holes of the valves.

So also the characteristic curve of the dynamo may serve two functions. When the scale on which it is drawn is known

it tells the horse-power at which the dynamo works; nay, can indicate at what horse-power the dynamo may be worked to the greatest profit. But even though the actual scale be not known, the details of the form of the curve afford definite information as to the conditions of the working of the machine; the degree of saturation of its magnets, the sufficiency of the field-magnets in proportion to the armature, and the goodness of the design in several respects.

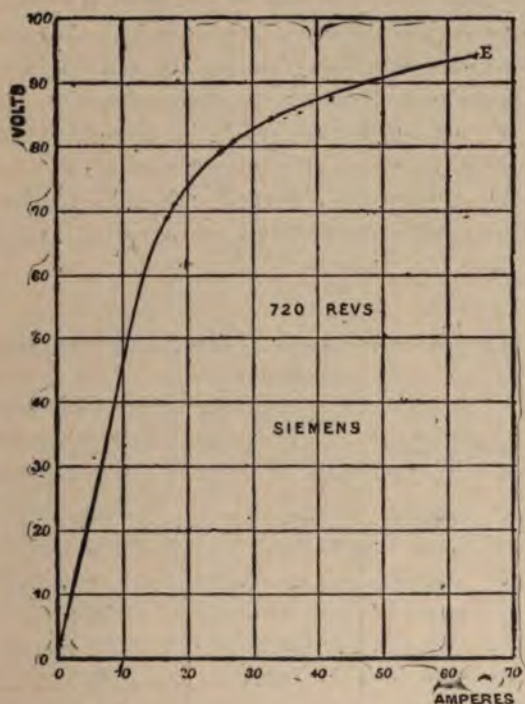


FIG. 127.—CHARACTERISTIC CURVE OF A SERIES DYNAMO.

The first self-exciting dynamos put into commerce were series wound; they were found to possess a most puzzling instability of behaviour, sometimes losing their current altogether, and refusing to excite themselves. This and other peculiarities were not understood until the curves of their performance were studied.

The suggestion to represent the properties of a dynamo machine by means of the characteristic curve is due to Dr. Hopkinson, who in 1879 described such curves to the Institution of Mechanical Engineers, and gave the curve of the Siemens dynamo reproduced in Fig. 125. The name of "characteristic" was assigned in 1881 by M. Marcel Deprez¹ to Hopkinson's curves; and the excellence of the name has been attested by its general adoption.

Dr. Hopkinson's object was to represent the relation subsisting between the electromotive-force and the current; he therefore constructed from observations a curve in which the abscissæ measured horizontally represent the number of amperes of current flowing, and the vertical ordinates the corresponding values of the electromotive-force. The following table gives the observed values *C* of the current, and *E* the electromotive-force, of a certain series-wound dynamo.

EXPERIMENTS ON SIEMENS DYNAMO AT SPEED OF 720 REVOLUTIONS PER MINUTE.

Current in amperes. <i>C</i>	Resistance in ohms. <i>R</i>	Electromotive-Force in volts. <i>E</i>
0.027	1025	2.72
0.49	9.3	3.95
1.45	5.83	7.73
16.9	4.07	68.4
18.2	3.88	70.6
24.9	3.305	79.5
26.9	3.025	81.1
32.2	2.63	84.4
34.5	2.43	83.8
37.1	2.28	84.6
42.0	2.08	87.4

¹ Vide *La Lumière Électrique*, Dec. 3, 1881; where, however, Deprez gives a method of observation that is open to the objection that it neglects the armature reactions.

It may be remarked that the electromotive-force E is the total electromotive-force generated in the machine, and must not be confounded with e the difference of potential between the terminals as measured by a voltmeter, or other similar instrument. In many cases we now prefer to plot e instead of E ; but that was not Hopkinson's original method. He determined E by measuring C and multiplying it by the total resistance of the circuit; for by Ohm's law $CR = E$. It should also be remarked that the dynamo was a "series dynamo," shunt-wound machines not having at that date come into vogue.

Before entering into other points, it may be worth while to consider the meaning of the curve. It begins at a point a little above the origin. This shows that there was a small amount of residual magnetism remaining permanently in the field-magnets. The curve ascends at first at a steep angle, then curves round and eventually assumes a nearly straight course, but at a gentler slope than before. As the speed is constant—it was maintained at 720 revolutions per minute in Hopkinson's experiments—the only variable of importance is the magnetism. As this rises and grows toward a maximum, so does the induced electromotive-force. We might therefore expect, as Hopkinson points out, that this curve should exhibit peculiarities of form similar to those of the curve which represents the relation between the magnetizing current and the magnetization of an electromagnet; and a comparison of Fig. 127, the "characteristic" of the series dynamo, with Fig. 86, the "magnetization curve" of an electromagnet, will suffice to reveal the analogy. It must, however, be pointed out that the magnetism is affected by the reaction of the armature.

It is possible for a dynamo to be made to draw its own characteristic by mechanically moving the pencil relatively to the paper (as in steam indicators) by means of two electromagnets, one of them being excited by the main current, the other being connected as a shunt to the terminals of the machine.

angular hyperbolas. For example, the 1-horse-power line will pass through all the points for which the product of volts and amperes is equal to 746. It will therefore pass through the point corresponding to 74.6 volts and 10 amperes; through 37.3 volts and 20 amperes; through 14.92 volts and 50 amperes, &c., because the product in each of those cases is equal to 746 watts or 1 horse-power. The 2-horse-power line

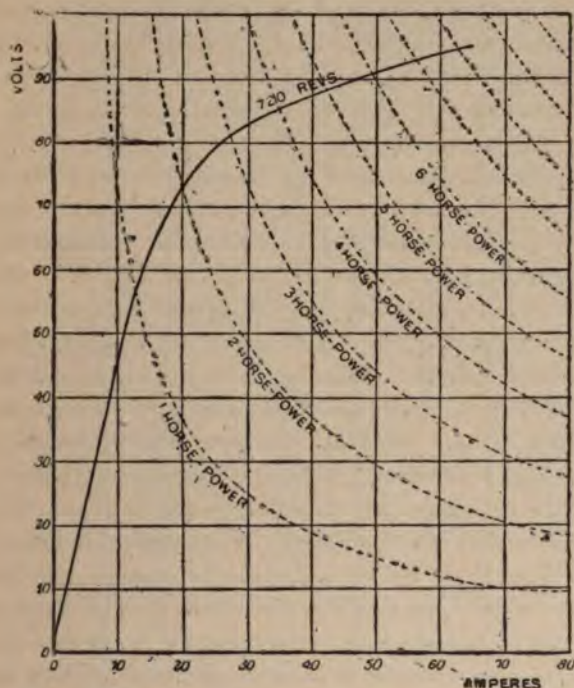


Fig. 128.—CHARACTERISTIC WITH HORSE-POWER LINES.

will pass through points whose product values are equal to 746×2 , and the other lines in the same way. Fig. 128 shows the characteristic of the Siemens machine, reproduced from Fig. 127 above, but with the horse-power line added.

In this case the volts plotted are the total electromotive-force E , of the dynamo, and therefore the horse-power represents the gross electric output. If instead of E we had

plotted the values of e , the volts at the terminals, we should have had a slightly different curve, representing the nett output in the external circuit available for useful purposes.

If the vertical and horizontal scales are not chosen equal, the horse-power lines, though hyperbolæ, are of course distorted.

“ External ” Characteristics or Terminal Potential Curves.—

The name *external characteristic* may be given for the sake of distinction to those curves which exhibit the relation between the potentials and the currents of the external circuit. In the series dynamo it is a simple matter to derive one of these curves from the other, provided the internal resistance of the machine (armature and field magnets) is known. In the Siemens dynamo examined by Hopkinson in 1879, and of which Figs. 127 and 128 give the total characteristic, the total internal resistance was 0.6 ohm. The curve is reproduced for a third time in Fig. 129, where it is marked “E.” Now to force a current of 10 amperes through a resistance of 0.6 of an ohm would require a difference of potential of 6 volts between its terminals. Looking at the curve, we see that the whole electromotive-force, corresponding to 10 amperes, was about 46.5 volts. Of this number, 6 were employed as mentioned, in overcoming the internal resistance, leaving 40.5 volts as the available potential between terminals. Further, when the current was running at 50 amperes, there must have been no less than 30 volts *lost* in overcoming the internal resistance of 0.6 ohm : and as the value of E for this current is 90.5 volts, there remain 60.5 volts for e . There are now two ways open to us of representing these matters on our diagram. They are both shown in Fig. 129. The line J is drawn through the origin, and through the values of 6 volts for 10 amperes and 30 volts for 50 amperes. (The tangent of the slope of the line J is equal to $6 \div 10 = 0.6$. We shall see later that this slope represents the internal resistance.) Then if the heights of the ordinates from the base line up to the line E represent total volts induced, and if the heights of the ordinates from the base line up to the line J represent the corresponding volts lost in overcoming internal resistance it

follows that the difference of potentials at the terminals will be represented by the differences of the ordinates between the lines J and E. This is the first way of representing those differences of potentials. The second way is to cut off from the tops of the ordinates portions equal to those of the line J. This amounts to subtracting the internal volts, which as shown in the algebraic theory are equal to $C(r_a + r_m)$, from E, and so obtaining the values of e . These are plotted out in the

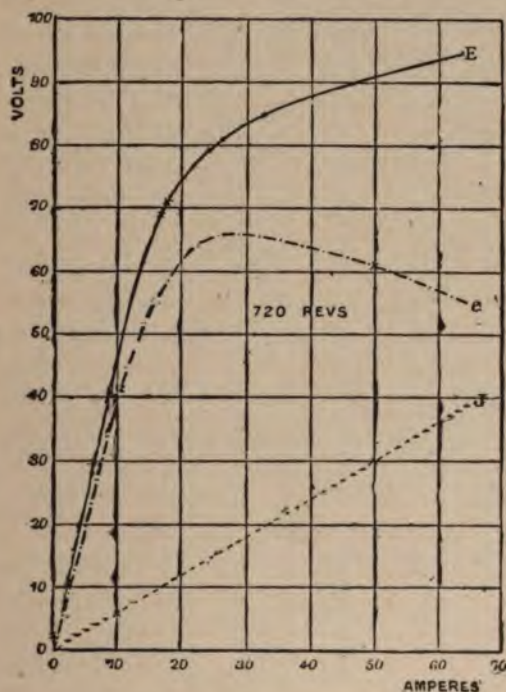


FIG. 129.—TOTAL AND EXTERNAL CHARACTERISTICS.

curve marked "e" in the figure; and as this curve represents the available electromotive-force in the external circuit, it obtains the name of *external characteristic* or *terminal potential curve*. As a matter of fact it is more usual to reverse the operation. The terminal potential values are easily observed with a volt-meter and the current with an ampere-meter. Then the external curve for e and C is plotted; and

by adding to the ordinates the corresponding values of the lost volts, we so obtain the curve for E and C. If there is permanent magnetism in the magnets, the characteristics will not start from the origin, but from a point a little above it.

Characteristics of Series Dynamo.—The Siemens dynamo of which the characteristic is given in Fig. 127 was a series dynamo. For the sake of comparison the characteristic is

given in Fig. 130 of an "A" Gramme machine also series-wound. This machine had, when it was measured by M. Marcel Deprez, 0.41 ohm resistance in the armature coils and 0.61 ohm in the coils of the field-magnets. Two characteristics are given; one corresponding to a speed of 1440, the other to a speed of 950 revolutions per minute. The horse-power lines are shown in dot also.

In the series dynamo the magnetization of the magnets increases with the current, and therefore, at first, the electromotive-force increases also, giving the first straight portion of the

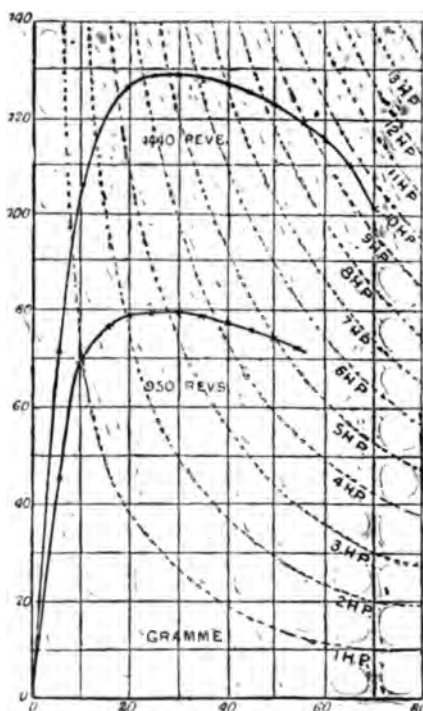


FIG. 130.—CHARACTERISTIC AT DIFFERENT SPEEDS.

curve. As the magnets approach saturation the curve turns, and, as the reactions due to the current in the armature now become of relatively great importance, flattens itself and ultimately turns down again; the increased lead of the brushes greatly adding to the effect. The fall in the characteristic is

always greater in the case of weak field-magnets. It also occurs most in those machines in which the core of the armature is more nearly saturated than are the cores of the field-magnets; for as with large currents the armature cores get saturated, the magnetic leakage becomes relatively greater.

One more curve of a series-wound dynamo is given in Fig 131. This is a small Brush machine (intended to supply a single arc light) of the early pattern, with solid iron ring, in which, owing to the peculiar arrangement of the coils (see p. 454), the reactions of the armature make themselves known by a very extraordinary down-bending of the characteristic. This is partly due to the arrangements for cutting out a pair of coils as they approach the neutral point. It will be noticed that the maximum horse-power of this small machine is $1\frac{3}{4}$ horse; and that this value is only obtained when the reactions have already set in. This diminution in the electromotive-force is in practice a real advantage. Should the machine be accidentally short-circuited while running, the reactions of the armature prevent the

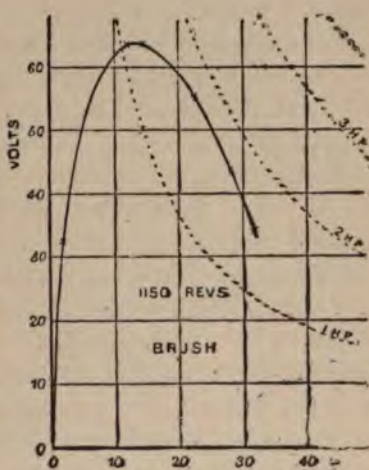


FIG. 131.—DROOPING CHARACTERISTIC.

production of an injuriously large current, which might overheat the coils. It is an advantage in machines for arc-lighting, where a nearly constant current is required, to employ machines with drooping characteristics, and to work them at this part of the curve (see p. 466).

Relation of Characteristic to Speed.—The electromotive-force generated in a rotating coil or armature would be strictly proportional to the field, were it not for the reactions of the armature. Now in a series dynamo, the field depends on the current; and, if the current is kept constant (by

adjusting the resistances), the field will also be constant even though the speed be varied. If therefore the characteristic of a machine be known at any speed, its characteristic for any other speed can be found by the very simple process of increasing the ordinates of the curve in a similar proportion. Take, for example, the case of the Gramme dynamo, of which a characteristic at the speed of 250 revolutions is given in Fig. 130. The characteristic at 1440 could be calculated from it by increasing the ordinates in the proportion of $\frac{1440}{950}$. Thus we see from the lower curve that when the

current was 20 amperes the electromotive-force was 79 volts. Then $79 \times 1440 \div 950 = 119.7$ volts. The actual electromotive-force observed at the speed 1440 and with current at 20 amperes was 127 volts. There is a slight discrepancy here, and indeed always; for dynamo machines behave invariably as if a certain number of the revolutions did not count electrically. If the number of "dead turns" (see p. 88) were here reckoned as 140, the number of volts calculated by theory would agree very exactly with that observed.

Resistance in the Characteristic.—In the characteristic we have volts plotted vertically and amperes horizontally. Now by Ohm's law, volts divided by amperes give ohms. How can this be represented in the characteristic? Suppose, for example, it is required to represent the resistance of the circuit corresponding to some particular current. Let Fig. 132 be the characteristic of the dynamo in question, and it is desired to know what is the resistance corresponding to the state of things at the point marked P. Draw the vertical ordinate P M, and join P to the origin O. The line P O has a certain slope, and the angle of its slope is P O M. Now P M is equal to the electromotive-force under consideration, and O M is the current. Therefore, by Ohm's law,

$$\text{Resistance} = \frac{\text{electromotive-force}}{\text{current}} = \frac{P M}{O M};$$

but

$$\frac{P M}{O M} = \tan P O M,$$

therefore the resistance = $\tan P O M$. Put into words, this is:—*The resistance corresponding to any point on the characteristic is represented by the tangent of the angle made by joining the point to the origin.* An easy way of reckoning these tangents is shown in Fig. 132. At the point on the horizontal line corresponding to 10 amperes erect a vertical line. A line drawn from the origin at an angle whose tangent is = 1 (namely 45°) would cross this vertical line at a point opposite the 10-volt mark. This point may then be called 1 ohm, and equal distances measured off on this line will constitute it a scale of resistances. In Fig. 132 the resistance corresponding to point P of the characteristic is seen to be about 1.2 ohm on the scale of resistances. Now P is placed at 51.3 volts, and the current is 43.2 amperes. Dividing one by the other, we get 1.18 ohm. Calculations are sometimes more conveniently made by graphic construction.

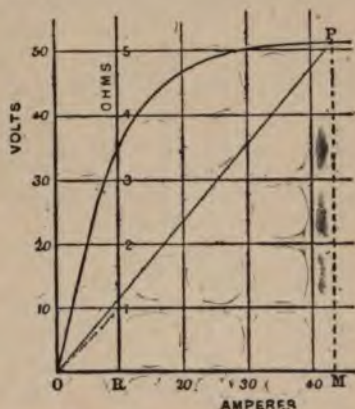


FIG. 132.—METHOD OF REPRESENTING RESISTANCE GRAPHICALLY.

If in the actual dynamo the resistance of the circuit were gradually increased, we should have the point P displaced along the curve backwards towards the origin, the volts and amperes both falling off, and the steepness of the line O P increasing. When O P arrived at a certain steepness it would practically form a tangent to that part of the characteristic which is nearly straight, and then any very small increase in the resistance would cause the dynamo to lose its magnetism, from lack of current to magnetize the magnets.

Resistance may be similarly represented on the characteristics of any dynamos; but if the characteristic is drawn for the *external* current and the *external* difference of potential, then the resistance so represented will be the *external* resistance.

Relation of Characteristic to Winding of Armature and Field-magnets.—Suppose the armature of a machine to be re-wound with a large number of turns of proportionally thinner wire. What will be the result at the same speed as before? The resistance will be increased somewhat, and the electromotive force also will be higher. Let Fig. 133 represent the characteristic of the machine as it was when there were X turns of wire on the armature. How must it be drawn when the number is increased to X' ? Let P represent a point corresponding to a certain strength of current. Taking the new armature, let the external resistance be varied until the current once more comes to the same value. The magnets are

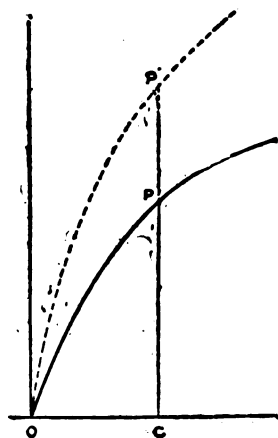


FIG. 133.

now magnetized exactly as strongly as before; but there are X' turns of wire cutting the magnetic flux, instead of X . The electromotive force will therefore also be greater in the like proportion. Draw therefore $P'C$ so as to have the proportion $P'C : PC :: X' : X$. All other points on the new characteristic can be obtained by similarly enlarging the ordinate in the same ratio.

It will be evident from this that increasing the number of turns of wire in the armature has the same effect as increasing the speed of driving. This shows that *slow speed*

dynamos (for use on ships, &c.) may be made to give the requisite electromotive force provided the number of turns of wire be relatively increased. This involves, however, a sacrifice of economy, because of the increase of resistance in the armature, or of prime cost if thicker wire is used.

The effect of altering the number of turns of wire on the field-magnets can also be traced out on the characteristic diagram. Suppose the number of turns in the magnetizing coil be S , and that we re-design the machine, increasing the number to S' turns. What will the result be? In this case

we shall get the same electromotive-force when driving at the same speed as before, provided the magnets be equally magnetized. But if the current goes S' times around instead of S we shall want a current only $\frac{S}{S'}$ as strong as before, to produce the same magnetization. To get the new characteristic then (see Fig. 134,) draw PE horizontally. $PE = CO =$ the current corresponding to electromotive-force E . Find P' such that $P'E : PE :: S : S'$; then the new characteristic will pass through P' . Similarly, all other points of

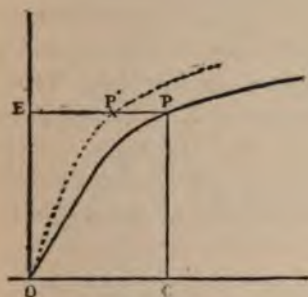


FIG. 134.



FIG. 135.

the new characteristic may be determined by reducing their abscissæ in a similar proportion.

It must be noted that these two processes are not admissible for the characteristics of shunt-wound machines.

Critical Current of Series Dynamo.—From the fact that the characteristics for different speeds differ only in the relative scale of the ordinates, an important consequence may be deduced. The first part of every characteristic for any speed is nearly straight up to a point where for that speed the electromotive-force is nearly two-thirds of its maximum value. When the current is such that the electromotive-force has attained to this value, any very small change either

in the speed of the engine or in the resistance of the circuit produces a great change in the electromotive-force, and therefore in the current; therefore since this critical case occurs always with the same current (see Fig. 135), this current—corresponding to the point on all the curves where the straight line begins to turn—may be called the “critical current” of the dynamo. This is the explanation of the puzzling instability remarked on p. 197. The series dynamo only “builds” its magnetism when the resistance is low enough, and when excited and running will “unbuild,” or lose its magnetism, if the resistance of the circuit is increased too much. Each series dynamo has its own critical current, and it will not work with a less one; for a less one will not adequately excite the field-magnets. Since with each speed the characteristic rises with a corresponding slope, there will be at each value of the speed one particular resistance at which the current will have the critical value; and the higher the speed the higher may be the resistance. There is no such thing as a critical resistance *per se*: for whether a resistance is critical or not depends upon the speed. *Neither is there any such thing per se as a critical speed for a series dynamo*; for whether the speed is critical or not, depends on the resistance of the circuit.

CHARACTERISTIC OF SHUNT DYNAMO.

For the shunt dynamo there are two separate characteristics; the *external characteristic*, in which the quantities plotted are the amperes of current in the external circuit and the volts of potential between terminals; and the *internal characteristic* in which the volts and amperes of the shunt circuit are plotted. The internal characteristic of the shunt dynamo is quite similar to the external characteristic of a series dynamo, and shows the saturation of the field-magnets. It is better to plot it with ampere-turns instead of amperes, because the magnetization depends on the number of turns in the coil as well as the amperes.

The external characteristic of a small shunt dynamo (the same described by the late Sir William Siemens before

the Royal Society in 1880, and by Mr. Alexander Siemens in the *Journ. Soc. Teleg. Eng.*, March 1880) is given in Fig. 136, and the horse-power lines are shown dotted. The utmost power of this machine at 630 revolutions was just under 2 horse-power with a current of 30 amperes, and an electro-motive-force of 47.5 volts.

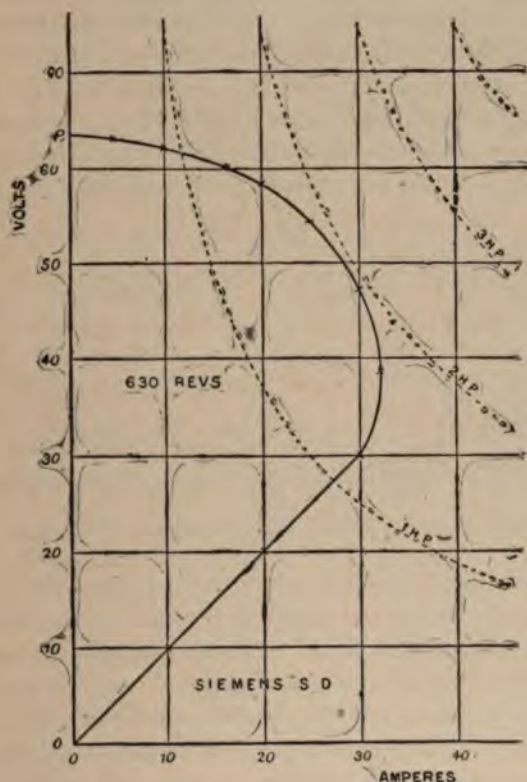


FIG. 136.—EXTERNAL CHARACTERISTIC OF SHUNT DYNAMO.

The curve of the shunt dynamo is curiously different from that of the series dynamo. It begins, on open circuit, at a point (marked *e*) where the volts are a maximum and runs slightly descending from the horizontal: then descends rapidly and returns towards the origin in a nearly straight line.

The straight portion represents the unstable state when the shunt current is less than its true critical value. The critical external current, if it can be so called, is in Fig. 136 about 30 amperes. The slope of the line which constitutes the last portion of the characteristic represents the resistance which for the particular speed may be termed the critical resistance, and in this case is about 1 ohm. Any less resistance will cause the magnets to lose their magnetism at once. Any greater resistance will at once run the electromotive-force up above the critical value—in this case about 30 or 31 volts. If the resistance of the external circuit becomes in the least degree altered, the electromotive-force and current will alter enormously. If the resistance be steadily increased (and the

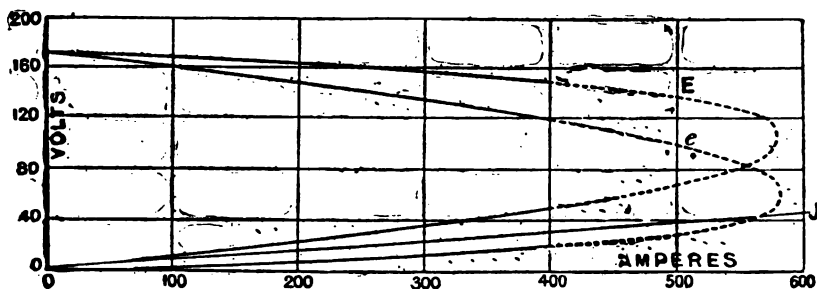


FIG. 137.—CHARACTERISTIC OF A SHUNT DYNAMO.

slope of the line from O to the curve be increased in steepness) the volts will go on steadily augmenting, and become a maximum when the external resistance is infinite, that is to say when the circuit is completely opened and the shunt coils receive the whole of the electromotive-force of the armature. Fig. 137 depicts the characteristic of a shunt-wound Gramme dynamo capable of giving 400 amperes. In this case the curve *e* represents the external characteristic, from which the curve *E* is calculated by adding to the ordinates portions equal to $r_a C_a$. As the conductors of the armature could not safely carry more than 400 amperes, the dotted portion of the curve represents results not actually observed. It is instructive to contrast the characteristic of the shunt dynamo with that of the series dynamo (Fig. 127). In the series dynamo, the

first part of the characteristic is a sloping line, and the tangent of the angle of its slope is also the critical resistance for the given speed. But the series dynamo will only work if the resistance of the external circuit is *less* than the critical value, and the shunt dynamo will only work if the external resistance is *greater* than the critical value. The contrast is even better shown by drawing a couple of curves in the two cases — not characteristics — showing the relation between the potential at terminals and the resistances of the external circuit. Fig. 138 shows this for a series machine, and Fig. 139 for a shunt machine. The electromotive-force of the



FIG. 138.

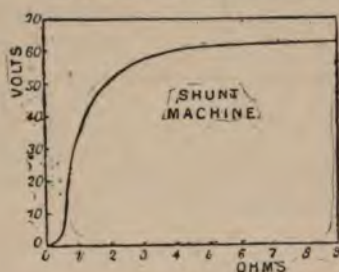


FIG. 139.

one drops suddenly when the resistance exceeds 2 ohms; that of the other rises suddenly when the resistance attains the value of 1 ohm.

In the shunt dynamo the characteristic for a double speed cannot be obtained as in a series dynamo by doubling the heights of the ordinates. For even if at a double speed we adjust the external resistances so that the external current is the same as before, we do not get a double electromotive-force because we do not get the same current as before round the shunt-magnet circuit. And if, on the other hand, we adjust resistances so that we get the same shunt current as before, and therefore a double electromotive-force, we do not get the same external current as before. If, however, we alter the external resistance, taking a larger current externally, so as to reduce the shunt current to its former value, the magnetization will remain as before. In that case the double speed will produce very nearly a double electromotive-force,

but the shunt potential may remain as before, the external current being nearly doubled. This is shown in Fig. 140, where $e a$ represents the external current in the first case, and $e A$ the external current in the second. $O A$ remains a

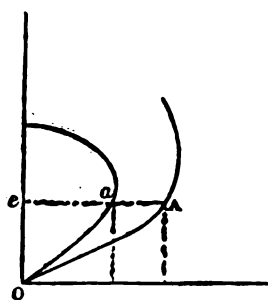


FIG. 140.

straight line, but at this higher speed the slope is less. From this latter circumstance it may be foreseen that at higher speeds the resistance may be reduced to a lower value before the critical state is reached at which the machine "unbuilds" itself, i. e. discharges the magnetism from its field-magnets.

Curve of Total Current in Armature.—In the shunt dynamo the current in the armature is equal to

the sum of the currents in the external circuit and in the shunt circuit ; or

$$C_a = C + C_s.$$

A curve showing the relation between C and e is easily obtained. In Fig. 141 let the curve $O m i$ be the "external

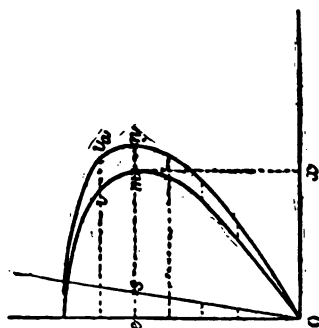


FIG. 141.

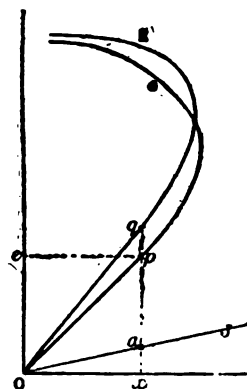


FIG. 142.

characteristic" at the given speed. Take any point on it such as m ; at that point the potential between terminals is

measured by the length of xm or Oe , and the current in amperes is measured by the length Ox or em . Now draw the line sO at such an angle sOx that its tangent is equal to the resistance of the shunt. Then es represents the current that will run through the shunt when the potential is Oe volts. Add on to the end of em a piece mn equal to es ; then the whole line en represents the armature current C_a when the potential has the value Oe . A set of similar points may be found giving the new curve Oni_a required.

Total Characteristic of Shunt Dynamo.—If the total electromotive-force E and the total current C_a be plotted out, we shall obtain the characteristic of the total electrical activity of the dynamo.

Draw, as in the preceding case, the curve for e and C_a . Let p be any point on the curve where the potential is px or Oe and the current ep or Ox . Then draw a line OJ at such an angle aOx that its tangent is equal to the resistance of the armature. Call the point where this cuts px , a . Then ax represents the number of volts required to drive the current Ox through the armature resist-

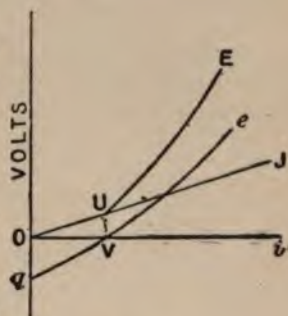


FIG 143,

ance. Add a piece qp equal to ax to the summit of the line px . Then the height qx represents the total electromotive-force E when the current C_a has the value represented by Ox .

Characteristic of Shunt Dynamo, with Permanent Magnetism.—If there is residual magnetism in the field-magnets, there will be an electromotive-force induced, even before the shunt circuit is closed. In this case the characteristic would begin at a point p , a short distance along the horizontal axis. In fact the machine behaves as though there were already at work some small electromotive-force (not to be plotted), which had the effect of setting up already a current through the machine, so that the machine excites itself up with currents that are, in the early (and unstable) stages of the magnetiza-

tion, proportional to the ampere-turns going round the shunt circuit, *plus* some imaginary ampere-turns causing the permanent magnetism. If there is on the field-magnet a second coil, by which an independent magnetization can be introduced, the same kind of result will follow: the characteristic will begin at some point, such as V, the electromotive-force due to the ampere-turns in the shunt being plotted out above O, whilst the length O *q* below represents the part of the electromotive-force due to the ampere-turns (real or imaginary)

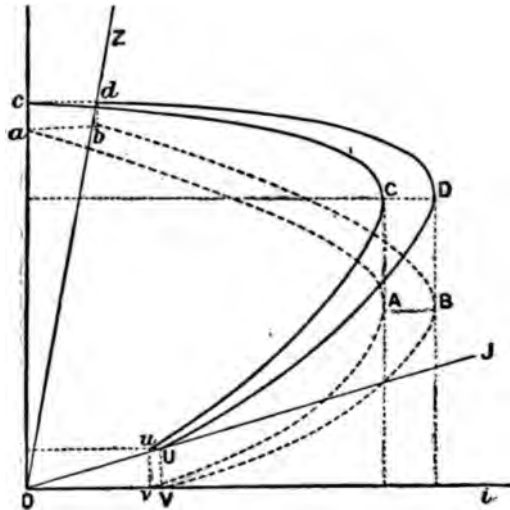


FIG. 144—FOUR CURVES OF A SHUNT DYNAMO.

of the independent magnetism; and O V represents the current which the machine will give when short circuited.

There will, in fact, be four curves for a shunt dynamo, namely, those in which the quantity plotted out are respectively *e* and C, *e* and *C_a*, E and C, E and *C_a*. Of these, the first is the *external characteristic*, and the fourth the *total characteristic*.

These four are depicted in Fig. 144, where they are named A, B, C and D respectively. If D is given, A can be obtained in the following way:—Let the lines O J and O Z represent respectively by their slope the resistance of the armature and

resistance of the shunt-winding; for example, if the shunt-resistance be 16, the line will pass through a point the ordinate of which represents 16 volts and the abscissa 1 ampere. Let this line meet the curve of magnetization at M . If we consider any point P on the curve, its ordinate PR will represent, according as we please, either the effective magnetism when the magnetizing current is OR , or the whole number of volts E induced in the armature; and the part of the ordinate QR will represent the difference of potential e . Clearly then PQ will represent $E - e$, that is to say, the volts lost in the armature, which are equal to $r_a C_a$. Now, if on the right of the diagram we lay out a line OJ at such an angle that the tangent of its slope represents the armature resistance r_a , then if V be taken so far along the horizontal axis that $VU = PQ$, the length OV will represent C_a . The most convenient construction is to project points P and

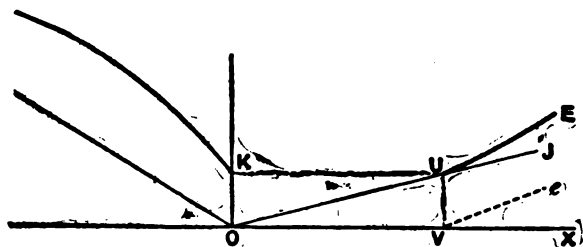


FIG. 146.

Q across to E and e , and from e draw eT , parallel to OU , meeting ET in T ; then drop a perpendicular from T giving the points t , U and V , where $Tt = UV$. T will be a point on the curve connecting E and C_a ; t a point on the curve connecting e and C_a . From the latter curve the external characteristic can be got as shown on p. 215. Of these hyperbolic curves the lower limb which returns towards O represents the unstable portion corresponding to the lower part of the magnetic curve. From the existence in the curves of a maximum value of C_a , where the curve turns round on the extreme right, it must not be inferred that the machine can yield this maximum current; on the contrary, the maximum current that the machine can safely give depends on the section of its armature wires, and these are—in the best machines—not intended to carry the current under such conditions. The working part of the curve is usually the top part (Fig. 145), and it will be obvious from the construction that the smaller the internal resistance, the further will the curve extend to

the right and the more nearly horizontal will the tops of both curves be; a good shunt-dynamo, with very little internal resistance, being *nearly* self-regulating for constant potential.

If there be no initial or residual magnetization, the curves will both pass through O; but neither of them will do so if there is initial or residual magnetization. In that case the curve of magnetization will commence above O at some point such as K, Fig. 146, and the lower ends of the two curves for E and e will end at points so far to the right that the width $UV = KO$. With almost every shunt dynamo it is found that if descending values of e are taken (at any given speed) e becomes zero, whilst C has still a definite value.

It will also be noticed that the limiting value of e depends on the slope of MO, that is to say, on the resistance per turn of the shunt coil; any diminution of the resistance per turn will raise E by forcing up to a higher degree the magnetization corresponding to a given value of e .

Contrast of Series Dynamo with Shunt Dynamo.—The difference between series dynamos and shunt dynamos in their behavior when the resistance of the current is increased or decreased, has already been touched upon in p. 213. In electric lighting, dynamos are usually required either (a) to supply glow-lamps arranged in parallel, in which case the dynamos must maintain a constant potential at the mains, or else (b) to supply arc-lamps arranged in series, in which case the dynamo is required to yield a constant current. In the case where the potential is to be constant, the current will vary with the number of lamps in parallel; in the second case, where the current is to be constant, the electromotive-force must vary as the number of lamps in series.

To understand the applicability of series or shunt dynamos to either of these tasks, it will be convenient to construct (either from experiment or from theory) comparative curves. In the case of parallel distribution, every additional lamp switched on across the mains adds to the conductance of the circuit an amount equal to its own conductance (*i.e.* equal to the reciprocal of its own resistance). It is therefore expedient to plot out together the values of e and of $\frac{1}{R}$. This has been

done in Fig. 147 for two dynamos, for each of which the maximum value of e was the same. It will be seen that for neither a series nor for a shunt machine does the value of e remain constant as the number of lamps across the mains is increased. The shunt machine gives the more nearly constant potential, but falls off as the number of lamps is increased.

In the case of single-circuit distribution to lamps in series, every additional lamp adds to the resistance of the circuit, and in this case it is expedient to plot out together the values of C and R . Fig. 148 shows the result for the two kinds of machine. It will be seen that neither machine gives anything like a constant current; but for the shunt machine there is

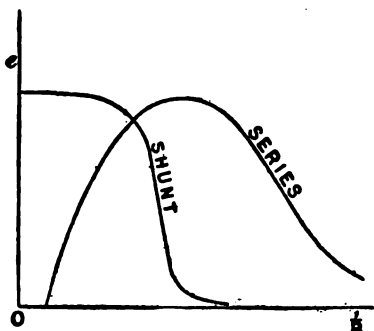


FIG. 147.

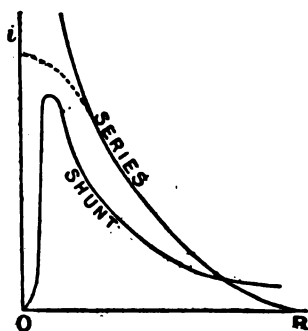


FIG. 148.

just one brief stage, namely, when its current is at the maximum, where the value is more constant than anything that the series dynamo can give. The dotted part of the curve corresponds to the case of a series dynamo so designed as to have a drooping characteristic (like Fig. 131, p. 205), which gives more nearly (with moderately small resistances) a constant current. But it is abundantly clear that something more than a simple series or simple shunt machine is requisite to give a real self-regulating machine for either purpose.

Further use of characteristics.—The following examples of the further use of characteristics are taken from Dr. Hopkinson's paper in the *Proc. Inst. Mech. Engineers* for April 1880.

Relation of Characteristic to Size of Machine.—Suppose that a certain dynamo of a given construction has for its characteristic the curve Oa (Fig. 149). What will be the characteristic of a dynamo built of precisely the same type, but with all its linear dimensions doubled? The surfaces will be four times as great, the volume and weight eight times as great. There will be the same number of turns of wire, but the length will be doubled and the cross-section quadrupled, and therefore the internal resistances will be halved. If the resistances were adjusted so as to give the same current as before, the new machine would have only half the intensity of field of the small one. But if adjusted to give the same intensity of field as before, the current will be doubled.

Now the magnetic flux will be increased fourfold, and therefore the electromotive-force will be four times as great. But we only wanted the current doubled. That is to say, the resistance will have to be doubled if the field is to be of the same intensity. To represent this state of things, take the point a on the characteristic of the small machine, and draw the ordinate am . Draw OM , double Om , and at M erect an ordinate AM four times the length of am . The resistance—the slope of OA —is double that of Oa . The new characteristic will pass through A . The points a and A are similar points with respect to the saturation of the iron of the magnets; and it is this which determines the practical limits to the economic working of a dynamo of given type at a given speed. Hence we see, with quadrupled electromotive-force and double current, the output

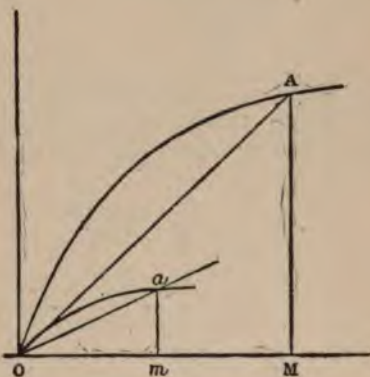


FIG. 149.

will be eight times as great as with the smaller machine when worked up to an equal saturation limit. These points may be compared with the discussion of the relation of size to efficiency on p. 108.

Application of Characteristics to Dynamos used in Charging Accumulators.—The following problem is of great practical importance:—*Suppose a dynamo is used for charging an accumulator, and is driven at a given speed, what current will pass through it?*

Dr. Hopkinson has given a solution of this problem for the case of a series dynamo. Draw the total characteristic of the dynamo (Fig. 150) for the given speed. Along OY set off OE to represent the electromotive-force of the accumulator, and through E draw the line CEA , making an angle with OX such that its tangent represents the resistance of the whole circuit, including the accumulators. This line will cut the characteristic in the points B and A ; and, if the characteristic be

repeated backwards, in C also. This negative branch of the characteristic is simply the characteristic of the dynamo when the current through

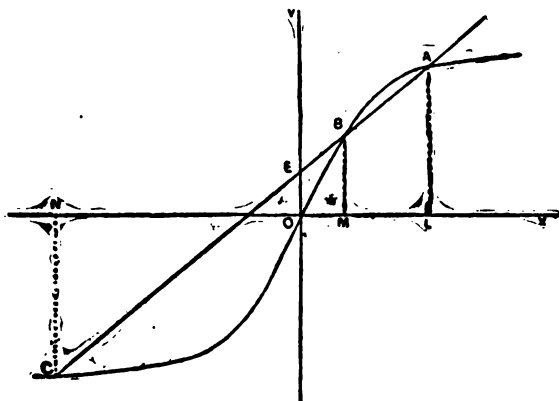


FIG. 150.

it is reversed, and its electromotive-force therefore also inverted. Then O L represents the actual current in the circuit ; O M represents an unstable current which might exist for a moment ; and O N represents the

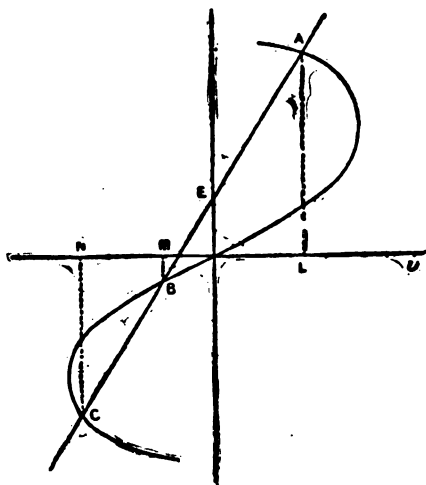


FIG. 151.

current which would traverse the circuit were the accumulators to overpower the dynamo and reverse it, as indeed frequently happens when series dynamos are so used. For it will be observed that if, as is the case when accumulators are reaching their full charge, their electromotive-force were to rise, or the resistance of the circuit to increase, the inevitable result would be to diminish the current O L, so that the magnetism of the field-magnets will also drop, thus diminishing the effective electromotive-force of the dynamo : and consequently the point A will be

brought nearer to the position of instability at the bow of the curve.

With the shunt dynamo the case is different. Let Fig. 151 represent the characteristic of the shunt dynamo, the external current being plotted along O X, and the total electromotive-force along O Y. Draw

the line C E A as before. Then it cuts the positive branch at A, and O L is the current in the main circuit. If, now, either the counter electromotive-force of the accumulators or the resistance of the circuit increases, the effect will be to move the point A to a higher point on the curve. The charging current O L may diminish, but the shunt current will increase or the effective electromotive-force A L will be increased. Therefore with the shunt dynamo there will be no likelihood of the accumulators overpowering and reversing the dynamo.

In the case of a series dynamo driving an arc-lamp, Fig. 150 also may be applied to explain the instability sometimes observed. The arc acts as though it had a counter electromotive-force, which, for steady arcs is not less than 35 volts. Hence if O E is set off to this value, the resistance of the rest of the circuit must be low enough for the sloping line E A to cut the curve above the "knee," otherwise the condition becomes unstable.

CHAPTER XI.

CONSTANT POTENTIAL DYNAMOS.

Conditions of Supply.—For some purposes—as for feeding a system of incandescent lamps in parallel—the current must be supplied from the mains at an absolutely *constant potential* or *pressure*; that is to say, the difference of potentials between the mains must be constant. This, of course, implies that the current delivered by the machine shall vary exactly in a ratio inverse to that of the resistance of the external circuit; increasing, as the resistance is diminished by adding to the number of lamps across the mains of the circuit. But we have seen that, owing to two causes—(1) internal resistance, (2) demagnetizing reactions of armature—the volts at the terminals at full load fall short of the value they would have (at the same speed and magnetization) at zero load. The *lost volts* increase with the load. Hence, means must be taken to compensate for the lost volts if the supply is to be maintained at a *constant pressure*. If a dynamo is to supply lamps at, say 100 volts, the pressure must not be allowed to fall to 97 or 96 volts when all the lamps are at work.

For some other purposes, as for supplying a set of lamps connected in a simple series, placed on one line, it is necessary to maintain in the line an absolutely *constant current*, no matter how many or how few lamps or motors may be at work. This, of course, means that when the resistance of the main circuit is increased by the switching-in of more lamps, the dynamo must put forth a proportionate increase of electromotive-force.

The two ends to be attained by regulation are therefore not only distinct, but incompatible with one another; a dynamo cannot possibly keep its electromotive-force constant, and at

the same time vary it in proportion to the varying resistance of the external circuit. The two systems are adapted to entirely different cases of electric distribution. Their theory is different; and the practical modes for carrying them out are different also.

Constant-current machines, as required for arc-lighting, and for glow-lamps in series, are described in Chapter XVIII. The present chapter will deal only with machines for supply at constant pressure.

There are various ways of governing dynamos so as to maintain either a constant potential or a constant current. Some of these methods involve hand regulation; others automatic switching in or out of resistances, to vary the excitation of the field-magnets; others, automatic adjustment of the brushes; and others, electrical governing of the speed. The chapter on Regulators deals with these. Let it be noted in the first place that the voltage of a given dynamo depends, as shown by the fundamental equation (p. 170), on three things—the speed, the number of armature-windings, and the magnetic flux: hence it follows that any one of these might be used to control the output of the machine. The speed can be changed by purely mechanical contrivances. The number of effective armature conductors can be changed by shifting the brushes forward beyond the neutral point. The magnetic flux can be varied by altering the magnetizing current that excites the magnetism, or by changing the disposition of the magnetic circuit.

In cases of isolated plant it may be convenient to apply a governor to so vary the speed in accordance with the demands on the circuit as to maintain a constant electric pressure; but this is not satisfactory when the engine has other work than driving a single dynamo. Those methods have been preferred which admit of the maintenance of a constant speed of driving. Throughout this chapter this condition will be assumed to hold good; and as a purely magnetic method of regulation is but little used we need only deal here with the methods that depend on varying the excitation of the magnets.

Hand Regulator.—In Edison's method of supplying mains at a constant potential a shunt dynamo is employed, a variable resistance, or rheostat, R , being introduced into the shunt-circuit (Fig. 152). A lever moved by hand, whenever the potential rises or falls below its proper value, makes contact on a number of studs connected with a set of resistances, and thus controls the degree of excitation of the field-magnets. To make the arrangement automatic the variable resistance should be adjusted by an electromagnet the coils of which are an independent shunt across the mains. The shunt dynamo, if well constructed, is, as shown on p. 212, nearly

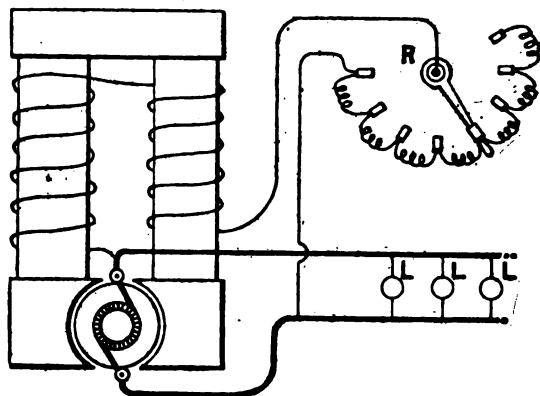


FIG. 152.—EDISON'S METHOD OF REGULATING.

constant in its voltage; the pressure at the terminals falls off very little at full load. With such a dynamo, but a small increase of exciting power is needed to make up for the lost volts at full load. The regulating rheostat is equally applicable to a separately-excited machine.

Self-regulating Machines.—The theory of self-regulation is extremely simple. Volts depend on the flux; hence, any drop in the volts can be compensated by increasing the flux. The problem then is how to make the main current, which as it increases causes the volts to drop automatically, increase the flux. It is clear that a compensating main-circuit coil of sufficient turns to produce the needed *additional* excitation,

must be wound upon the field-magnet. The compensating coil must obviously be thick enough to carry the main current, and usually consists of few turns. If the machine is shunt-wound to begin with, and a compensating coil in series with the armature is thus added, the combination is usually termed a "compound" winding. The term "compound dynamo" was introduced by Messrs. Crompton and Kapp to signify a dynamo with mixed series and shunt-winding, by analogy with the engineers' term "compound engine" for a steam-engine working with both high- and low-pressure cylinders. A compensating series-coil is, however, equally applicable to any well-designed dynamo in which the initial magnetism is independently excited. The following combinations are possible :—

- (i.) Series regulating coils + permanent magnets to excite the field initially with an independent constant magnetization.
- (ii.) Series regulating coils + an independent current circulating in separate coils round the field-magnets, to produce an independent constant magnetization.
- (iii.) Series regulating coils + an independent current circulating in the main circuit (and generated either by a battery or by an independent magneto-dynamo) having the effect of partly exciting the field-magnets with an independent constant magnetization.
- (iv.) Series regulating coils + shunt-magnet coils supplied by a portion of the current of the machine itself, thereby partly exciting the field-magnets, with an independent and nearly constant magnetization.
- (v.) Alternate-current dynamos may be compounded by providing them with regulating coils supplied with a current derived (by a suitable transformer) from the main-circuit current, and proportional to it; the derived currents being first sent through a rectifying commutator. The independent magnetization may be derived either from an auxiliary exciter, or from a separate coil or group of coils in the armature, or, in fact, by another transformer, the primary of which is placed across the mains as a shunt; in either of the latter cases the current being properly commuted.

Theoretically, several other self-regulating combinations are possible; for example, a machine with a long armature lying between two separate field-magnets, one independently excited, the other in series; a series machine with unsaturated magnets combined with a (quasi-independent) series machine with over-saturated magnets on the same shaft; a series machine having two sets of field-magnet poles at different leads, one of the sets of poles being the series-excited set, the other excited independently, or in shunt circuit, &c.

THEORY OF SELF-REGULATION.

In considering the theory of self-regulation we shall proceed as follows:—First find an expression for the pressure at the mains. This will, in general, consist of three terms. Secondly, we shall consider these three terms as to whether their factors are constants or variables. Then, having ascertained which of the terms contain variable factors, we must consider what conditions must be laid down (such as prescribing a particular speed or a particular number of windings) in order that the terms containing variable factors shall disappear. These conditions will be embodied in an “equation of condition,” which will be then discussed. In general it will be found that if the speed is prescribed beforehand, there will be a certain “critical” number of regulating coils to be deduced; or, on the other hand, if the number of regulating coils is prescribed beforehand, there will be a particular or “critical” speed at which self-regulation holds good.

It is possible to treat the theory either algebraically or geometrically. Both methods will be here used.

Case (i.) Series Regulating Coils + Permanent Magnets (compare p. 55).—If the field-magnets are partly permanently magnetized, or if there are permanent steel magnets in addition to the electromagnets, giving an initial field, we may denominate the initial flux as N_1 .

Now the fundamental equation of the series dynamo is

$$E = n Z N,$$

and the difference of potential or pressure at the terminals is found by deducting the lost volts ; or

$$e = E - (r_a + r_m) C.$$

But N , the number of magnetic lines that pass through the armature at any instant, is made up of two parts, the permanent independent part N_1 , and a part depending upon the current C , and equal to

$$\frac{4 \pi S_m C \div 10}{\sum \frac{l}{\mu A}} ;$$

where S_m is the number of turns in the compensating coil, l the length of the magnetic circuit, A its cross section, and μ the *average* value of the permeability (see p. 120) between the two extreme values that it has when C is zero and when C is at its maximum. If for brevity we write

$$\frac{4 \pi}{10} \sum \frac{l}{\mu A} = q,$$

we may then write the variable part of N as $q S_m C$; and therefore,

$$N = N_1 + q S_m C ;$$

and we get, as the complete expression for e ,

$$e = n Z (N_1 + q S_m C) - (r_a + r_m) C,$$

or

$$e = n Z N_1 + n Z q S_m C - (r_a + r_m) C.$$

The expression on the right-hand side of this equation consists of three terms, of which the first contains the speed and two constants as factors. The last two contain a variable, the current, and one of them also contains as factors the speed n and the number of regulating coils S_m . If S_m is prescribed beforehand, then the particular speed at which the dynamo is self-regulating will be clearly that speed at which the expression for e will contain nothing but constants. If n is prescribed beforehand, then we must vary S_m so as to eliminate

the terms that contain the variable factor. Since the two last terms are of opposite sign, it is clear that by varying S_m or n , or both, the value of $n Z q S_m$ may be made numerically equal to $r_a + r_m$. Then at the constant speed, which we will call n_1 , the last two terms will cancel one another out, or,

$$n_1 Z q S_m C - (r_a + r_m) C = 0.$$

That is to say, S_m and n_1 must be such that

$$n_1 Z q S_m = r_a + r_m \quad [\text{XIII.}]$$

This is the equation of condition.

If the condition laid down in this equation is observed, then the last two terms for e disappear, and we have simply,

$$e = n_1 Z N_1 = a \text{ constant.}$$

Having thus proved that, at the given speed, e is a constant, it is worth while to inquire what it is that determines the value of e . Clearly e is directly proportional to N_1 , the initial flux. Therefore, we can arrange that the dynamo, still driven at the given speed, shall give any pressure we please, within limits, provided we alter N_1 in the requisite proportion.

Suppose that the speed is prescribed by mechanical considerations, then the proper or critical number of regulating coils is given by the expression

$$S_m = \frac{r_a + r_m}{n_1 Z q}. \quad [\text{XIV.}]$$

This is instructive. The higher the internal resistance of a dynamo the greater must be the number of the regulating coils in series, if it is to be self-regulating.

Returning to the equation of condition, we will write it in the second form—

$$n_1 Z q S_m = r_a + r_m,$$

which for a given number of series coils gives us as the value of the critical speed,

$$n_1 = \frac{r_a + r_m}{S_m} \cdot \frac{1}{Z q},$$

and this speed will be higher the greater the internal resistances are.

Lastly, we may write the last equation in the following way,

critical speed = $\frac{\text{total internal resistance}}{\text{number of turns of series coils}} \times \text{a quantity}$
depending only on the armature windings and on the magnetic circuit and its working permeability within the range for which regulation is required.

So far we have assumed that the only cause of drop of pressure that needed to be compensated for was that due to internal resistances. But the drop of pressure due to the demagnetizing action of the armature is in modern machines a consideration of even more importance. To take account of this action we must remember that if the angle of lead λ is known, the demagnetizing belt of conductors (see p. 85) will be that comprised within an angle of 2λ , namely $Z \frac{\lambda}{180^\circ}$.

And each such conductor carries $\frac{1}{2} C$ amperes, making the demagnetizing ampere-turns $Z \lambda C \div 360^\circ$. Or, if the number of armature conductors within the angle λ is called D , the demagnetizing ampere-turns will be $2D \times \frac{1}{2} C = DC$. As, however, these turns are situated over the armature, whilst the compensating coils are wound on the field-magnet, their number will need to be greater in proportion approximately to the leakage coefficient v (see pp. 148 and 346). Hence we shall have to increase S_m , the series coils, from the value found above to the value

$$S_m = \frac{r_a + r_m}{n_1 Z q} + D v. \quad [\text{XV.}]$$

Case (ii.) Series Dynamo + Separately-excited Coils (see "*Series and Separate*," Fig. 44, p. 55).—In this case there is an initial magnetism due to a separate exciting current.

If we call the number of magnetic lines due to the independent excitation N_1 , the same argument holds good as in the preceding case, and the same conclusions. N_1 will not, however, be really a constant, for the effect of the introduction of a constant amount of magnetizing force will vary with the degree of saturation

resulting from the *whole* magnetizing force. If, however, the average working permeability throughout the range of regulation is taken into account in the calculation of N_1 as well as in that of S , then any falling-off in the effect of the independent exciting current is implicitly provided for.

Geometrical Demonstration of Cases (i.) and (ii.).—On p. 185 it was shown how the values of the potential at terminals fall off in magneto and separately-excited dynamos as the current increases, e always being less than E by an amount equal to $r_a C$.

To represent the facts, let $O X$ and $O P$ be taken as the axes for plotting out amperes and volts, and let $O P$ (Fig. 153) represent the electromotive-force ($E = n_1 Z N_1$) due to the permanent or independent magnetism, as measured when no current is running through the armature. Now, assuming that the armature reactions are small enough to be neglected, E will at constant speed

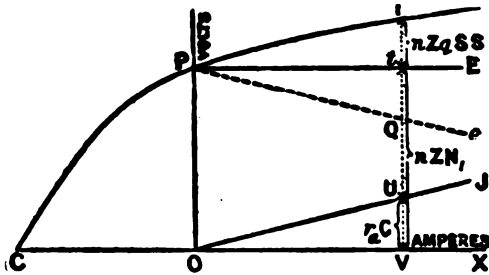


FIG. 153.

remain the same with all currents, but e will drop. From O set off the line OJ at an angle such that its tangent represents the internal resistance of the machine. Now consider the case when the current C has the particular value corre-

sponding to the length O V. The height U V will be the drop in the external volts; for $U V = \tan U O V \times O V = r_a C$. Cut off from t V a portion, t Q = U V, and Q V will represent e . While the curve for E and C is approximately a horizontal line, the curve for e and C (the external characteristic) falls, as shown by the dotted line. Any point on the e curve can be got from the E curve by simply deducting from the height a piece equal to the corresponding width across the triangle J O X. Now it must be obvious that if when the E curve is horizontal the e curve slopes downward, we must use an E curve that slopes upward by a precisely equal amount, if we want to get a horizontal e curve; that is to say, if we want to get constant potential. How are we to get an upward sloping E curve? Remember that at a given speed, n_1 , the value of E is $n_1 Z N_1$, where N_1 means that the magnetic circuit has somehow (either permanently or by a separate current) been excited up to such a degree that N_1 lines go through

the armature. The same plotting that serves for volts will serve for values of N by choosing the appropriate scale; or, $O P$ may represent N_1 . Therefore P is a point on a curve of magnetization, which will rise still higher if only we put on more ampere-turns of excitation. Therefore all that is required to be done is to put on the magnets a coil in series, having such a number of turns S_m that the ampere-turns $S_m C$ will have the effect of raising the magnetism in the right proportion; in fact, so that $T t$ shall be equal to $U V$. We have now got an E curve which slopes up—not quite a straight line, to be sure, but such that when we subtract the volts required to drive the current through the armature resistance, we get an e curve that is approximately level.

Comparing the algebraic and geometric methods, we see that $t V$ corresponds to $n_1 Z N_1$; $T t$ to $n_1 Z q S_m C$; and $U V$ to $r_a C$, or if the resistance of the added series coil is included in the slope of the line $O J$, $U V$ will correspond to $(r_a + r_m) C$.

Case (iii). Series Dynamo + Independent Electromotive-force thrown into the Main Circuit.—This really comprises two cases; where the independent constant electromotive-force is due to a battery, and where it is due to a separate magneto machine driven at a constant speed ("Series and Magneto," see p. 55). The argument is the same, however, for both cases. Fig. 154 will represent either case.

The solution is identical with the preceding cases, except that there are now three resistances internal to the arrangement to be compensated.

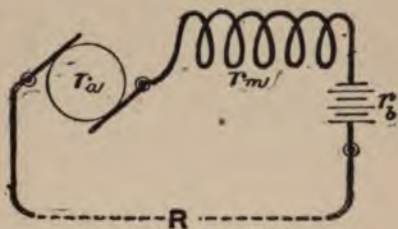


FIG. 154.

Case (iv.) Series Regulating Coils + Shunt Exciting Coils: "Compound Winding."—The compound-wound dynamo may be regarded as either a series dynamo to which some shunt windings have been added, so as to provide an initial magnetization, or as a shunt dynamo to which some series windings have been added to compensate for the drop of potential at the terminals. There are two possible methods of connecting the shunt coils to the dynamo, and the propor-

tions differ slightly in the two cases. In the "short-shunt" method (see p. 56) the shunt coils are joined as a shunt to the armature part of the dynamo only, being connected across from brush to brush. In the "long-shunt" method the shunt coils are connected across the terminals of the machine, and may, therefore, be regarded either as a shunt to the external circuit, or as a shunt to the armature and series coils together. In the former arrangement the current through the shunt is not constant, because though e may remain fairly constant, the potential at the brushes does not, but increases when the external circuit's resistance decreases. In the latter arrangement the current through the shunt is constant if e is constant, and the case becomes one analogous to those already discussed,

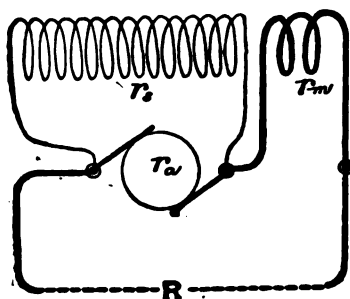


FIG. 155.

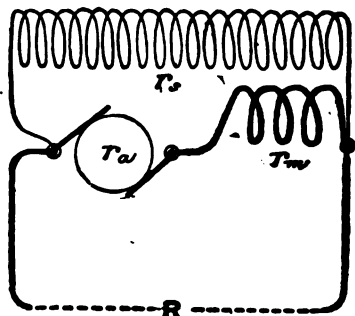


FIG. 156.

of an independent constant excitation. The connections of the short-shunt method are indicated in Fig. 155. In a well-designed dynamo it makes very little difference whether the shunt is connected across the brushes or across the terminals of the main circuit. The connections of the long-shunt arrangement are as shown in Fig. 156. The calculations for the two cases are practically identical, and involve the same kind of arguments. That for long-shunt is a little more simple, and is accordingly given.

We have then

$$E = n Z N; \quad \dots \quad (1)$$

$$e = E - (r_a + r_m) C_a \quad \dots \quad (2)$$

and as the magnetism depends on the total number of ampere-turns of excitation, we shall write,

$$N = q (S_s C_s + S_m C_a); \dots \dots \dots (3)$$

where q has the same signification as before (p. 229), namely

$$= \frac{4\pi}{10} \frac{\Sigma l}{\mu A};$$

or more strictly is the variable number representing, at the various stages of magnetization, the numerical ratio between flux and excitation for the magnetic circuit of the particular dynamo. For the present purpose it is also necessary to consider the value which q has when the external current is zero, and when the only excitation is that due to the shunt: this may be called q_0 . Then the initial flux on open circuit will be:—

$$N_0 = q_0 S_s C_s$$

Then from the three equations we have

$$e = n Z q S_s C_s + n Z q S_m C_a - (r_a + r_m) C_a.$$

Now here we have three terms, the first containing, as factors, the speed (which may be kept constant), and the shunt current C_s which will be made constant if e can be made constant; the second contains the speed also as a factor; the second and third both contain the variable current C_a . The two variable terms are of opposite sign. Now e cannot possibly be a constant, when two of its terms contain a variable as factor, unless the coefficients of that variable factor are such that they make those two terms cancel one another; e cannot be constant unless either the speed n or the windings S_m , or both, are so adjusted as to fulfil this. But these can be varied so that it is possible for the two coefficients to be equal, viz.—

$$n Z q S_m = r_a + r_m.$$

This is then one of the two equations of condition; and the critical number of series-turns at the given speed will be

$$S_m = \frac{r_a + r_m}{n} \cdot \frac{1}{Z q}.$$

Or, if S_m is prescribed, the critical speed will be

$$n = \frac{r_a + r_m}{S_m} \cdot \frac{1}{Z q}.$$

If this condition be observed, then e will be constant and have the value

$$e = n Z q S_s C_s.$$

But this would leave e indeterminate, since $C_s = e \div r_s$. But we may reflect that though this equation might not give us the value of e , there will nevertheless be a determinate value for it, namely, the same value that e would have when there is no current taken from the dynamo at all, but when it is running on open circuit only. Under these conditions the value of e will be

$$e = n Z N_o - (r_a + r_m) C_s;$$

or, since here q has the value q_o ,

$$e = n Z q_o S_s C_s.$$

But $e = C_s r_s$, whence we get

$$n = \frac{r_s}{S_s} \cdot \frac{1}{Z q_o}.$$

Comparing this value of n with that obtained in the first equation of condition, we get

$$\frac{r_s}{S_s q_o} = \frac{r_a + r_m}{S_m q};$$

whence, finally, as the *second* equation of condition,

$$\frac{S_s}{S_m} = \frac{r_s}{r_a + r_m} \cdot \frac{q}{q_o}.$$

As q_o is proportional to μ_o the initial permeability when the shunt only is at work, and q proportional to the average permeability μ for the range of working between zero current and maximum current, it follows that if there were no alteration of saturation, $q_1 \div q_o$ would equal 1. In the former editions of this work, wherein the theory of compounding was expressly based

upon the supposition that there was no saturation—or in other words, that the permeability was constant—the formulæ obtained were admittedly incorrect for this reason. Dr. Frölich found for a certain Siemens compound dynamo,

$$\frac{S_s}{S_m} = 17.7, \text{ whereas } \frac{r_s + r_a}{r_a + r_m} = 61.9.$$

From which it is clear that μ_o must have been about 3.5 times as great as μ_1 ; in other words, this machine had an insufficient quantity of iron in its magnets or armature core, or in both. This dynamo must have been both badly designed and of low efficiency; r_s ought to have been not 61.9, but at least 300 times as great as $r_a + r_m$.

To compensate for the demagnetizing action of the armature, additional turns are required in the series coil, as explained above on p. 231. To make the last set of formulæ complete S should be replaced by $S - D v$.

Over-compounding.—It will be noticed that, apart from the demagnetizing action of the armature, the amount of excitation to be provided for by the series coils is always proportional to the resistances that are in the main circuit and *internal to the points for which the constant difference of potential is desired*; this renders it possible, in a case where the mains leading from the dynamo to the lamps are long, so to compound the dynamo by adding more coils in series as to give a constant potential, not at its terminals, but at the distant point of the circuit where the lamps are to be used. This is a most valuable circumstance in all cases where the lamps are far from the dynamo, as in the lighting of mines from machinery at the surface; for then by *over-compounding*, one can obtain a constant pressure, not at the terminals of the dynamo, but on the mains at some point in the midst of the lamp-network. There is another advantage in over-compounding, namely, that when the full load comes upon a machine, the engine, however carefully governed, generally slows down a little, tending to produce a further drop in the voltage. As an example of over-compounding it may be mentioned that the 6-pole street-tramway generator, described on p. 433, required about 4000 ampere-turns per pole on

open circuit, but had a series-winding which allowed an additional 6000 ampere-turns per pole at full load.

Arrangements of Compound Winding.—Compound windings may be arranged in several different ways. If wound on the same core the shunt coils are sometimes wound outside the series coils: as frequently the series coils are outside the shunt. It is advisable to keep down the resistance of the series coils, as they will form part of the main circuit; whilst the additional resistance necessitated by winding the wire in coils of larger diameter is not altogether a disadvantage in a shunt coil. In the former editions of this work the recommendation was made to wind the series coils nearer the pole than the shunt coils. If the magnetic circuit through the ironwork be good, the position of the coils makes little difference.

Practical Process for Compounding.—It is clear from the foregoing paragraphs that the compound machine, when run on open circuit, with only the shunt-current flowing, must give the same potentials at its terminals as it is to give as a compound machine. Hence this leads to the following practical process for compounding. Let the armature of the machine be run at the proper speed dictated by mechanical considerations, and let a voltmeter be applied at the terminals. Two experiments are then necessary. First, by means of temporary coils, having a known number of turns wound on the field-magnets, and furnished with measured currents from some accumulators or another dynamo, ascertain the number of ampere-turns that will suffice to excite up the magnets to this point. From this S_s can be determined; for C_s is known beforehand, say 2 per cent. of the whole current at full load. Secondly, put into the main circuit some resistance to represent the maximum load of lamps, and while the machine is running at its proper speed, ascertain, using still the temporary coil and accumulators, how many ampere-turns of excitation are needed in total when the machine is doing full work. Subtract from this the value of $C_s S_s$ obtained in the first experiment, and the remainder gives the number of ampere-turns which the series coil must furnish; and as the

maximum current is known, S_m can at once be calculated. The same process suits for over-compounding, the excitation at full load being raised until the volts at terminals rise to the higher number of volts that will allow for the drop in the leads.

Design of Constant Potential Machines.—It is obviously of importance in such machines that the iron parts should be so designed that (1) the characteristic should be as nearly straight as possible in that portion of it corresponding to the working range of currents for which regulation is desired; (2) that it should not turn down. Consequently, it is of importance in such machines that there should be just so much iron in the magnetic circuit that the current due to the shunt should carry the initial magnetization over the knee of the curve of magnetization; and that the reactions due to the armature currents should be small. Also, of course, the resistance of the armature should be kept as small as possible.

Characteristic of Compound Dynamo.—In the original theory of constant potential machines devised by Marcel Deprez, the argument was based upon the absence of saturation, and the presence of an initial independent magnetization. The following was the argument of Deprez. If there is a permanent excitement of magnetism quite independent of that due to the main-circuit coils of the dynamo, the characteristic (Fig. 157) will not start from O, but from some point above it depending on the amount of independent magnetization and on the speed. Let the starting-point be P. O P is the electromotive force between terminals when the main circuit is open, but there is no external current until the circuit is closed, and then the characteristic rises in the usual fashion from P to Q. Draw O J at the proper slope to represent the resistance of the armature and series coils together. Now consider a line O E drawn at such an angle that the tangent of its slope represents the total resistance of the circuit at any parti-

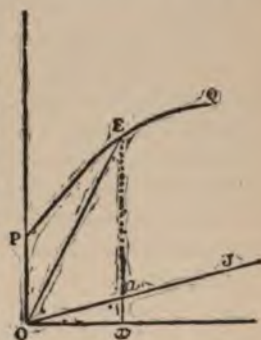


FIG. 157.

cular moment. Then $E x$ is the total electromotive-force at that moment, and a part of this, equal to $a x$, will be employed in driving the current $O x$ through the resistance of armature and series coils. The remaining part $E a$ represents the difference of potentials between the terminals of the external circuit. So the problem resolves itself into this: how to arrange matters so that $E a$ shall always be of the same length as $O P$, no matter how much or how little the line $O E$ may slope. Clearly the only way to do this is so to arrange the speed of the dynamo that the part from P to Q shall be parallel to $O J$. If the speed is reduced exactly to the right amount the inclination of the characteristic will be equal to that of the line $O J$. Then, as shown in Fig. 158, the potential between the terminals will be constant. It will be seen that this agrees with the deductions arrived at in the algebraic treatment of the question: namely, that the critical speed is

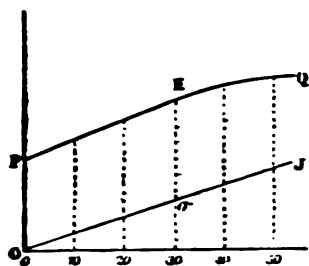


FIG. 158.

proportional to the internal resistance; and that the constant difference of potential $E a$ is equal to that due to the independent magnetization $O P$ at the critical speed.

It should also be noticed that if the part of the characteristic be not straight, that is to say, if the field-magnet cores are becoming saturated, the regulation cannot be perfect. If the line $P Q$ be curved, then the potential for large currents will not be equal to that for small currents.

If, in the practical process for winding the magnets, the coils have been wound so as to make e the requisite number of volts, both on open circuit (i. e. at $O P$), and at another point (say at $Q J$), when the dynamo is feeding its maximum load, then there will in general be a slightly greater potential for intermediate loads, owing to the slight convexity of the curve between P and Q .

The above argument holds good whether the independent excitation be due to permanent magnetism or to a combination with separately-exciting coils (see pp. 55 and 231), or to shunt-exciting coils. In the latter case $O P$ represents the potential at terminals due to shunt circuit alone.

The case of the "compound" dynamo is worth looking at from another point of view also. On p. 213 two curves—not characteristics—are given, showing the relation of electromotive-force to

external resistance in a series machine and in a shunt machine. One begins at a certain height and falls when the resistance has attained a certain value; the other begins low and rises when the resistance has attained a certain value. It is conceivable that if a dynamo were wound with both shunt and series coils, so that each worked up to the same potential and that they were so proportioned that the number of ohms at which one fell should be the same as that at which the other rose, then the compound machine should, as indicated in Fig. 159, give as a result of the double-winding, a constant potential.

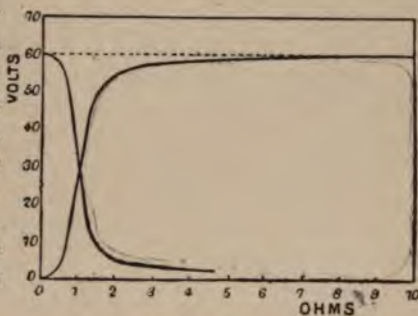


FIG. 159.

External Characteristics of Self-regulating Dynamos.

Simultaneous observations of the external current C and the external potential e enable us to plot the external characteristic; which in a perfectly self-regulating dynamo would be a horizontal line. If the number of regulating coils in series is too small, the characteristic will fall as the current rises; if too large, will droop slightly at the end near the origin. This latter case, however, is not always a disadvantage, for with machines worked singly on an engine the speed often rises in consequence of imperfect governing when the load on the dynamo is small.

Esson's Observations.—Mr. W. B. Esson has examined why it is that compound dynamos wound so as to be self-regulating for a given speed, regulate fairly well at any speed within considerably wide limits. The explanation he gives depends upon the saturation effect in the iron. If the magnetism were strictly proportional to the ampere-turns of excitation, there would be

literally a critical speed. The approximate rule $\frac{S_m}{S_s} = \frac{r_a + r_m}{r_s}$ gives

the number of series coils much too low, for when the shunt coil has already excited a certain degree of magnetization, the series coil cannot produce a proportionate increase owing to the lesser permeability. In a series machine (designed to give a current of 20 amperes), the electromotive-force added to the machine by increasing the exciting current from 5 to 10 amperes is much greater than the electromotive-force added by increasing the cur-

rent from 10 to 15 amperes. Again, a 100-volt machine (self-regulating), in which therefore the shunt gave excitement enough for 100 volts on open circuit, had series coils upon it which were able, when the shunt was removed and the full current on, to give 60 volts between terminals. The value of the series coils to excite magnetism is diminished as the excitation due to the shunt is increased. All this is, of course, due to the diminution in permeability of the iron of the machine as the degree of saturation increases. From this it follows that a certain relation must subsist between the speed of the machine and the degree to which the magnets are excited by the shunt coil. But the magnetism furnished by the shunt coil also depends on the speed, and increases with it. If, therefore, at one speed this relation is such as to produce self-regulation, the relation will be almost equally true at other speeds.

Engineers desiring further information on compound winding of dynamos, are referred to a series of articles in the *Electrician*, in 1883, by Mr. Gisbert Kapp; also to two articles by Mr. Esson in the *Electrician* of June 1885. Articles by M. Hospitalier in *L'Électricien*, and by Herr Uppenborn in the *Centralblatt für Elektrotechnik*, should also be consulted; and the student should above all read the series of papers published by Dr. Frölich in the *Elektrotechnische Zeitschrift* for 1885, and a still more remarkable paper by Professor Rücker in the *Philosophical Magazine* of June 1885. Some account of these was given in the Appendices of the third edition of this book. The latest contributions to this question are by C. Zickler, *Centralblatt für Elektrotechnik*, ix. 264, 1887, and M. Baumgardt, *ib.* x. 281, 1888; and by Dr. Louis Bell, in the *Electrical World*, xvi. 383, 1891.

CHAPTER XII.

ON WINDING OF ARMATURE (CONTINUOUS CURRENT).

THIS chapter is devoted to the theory of the ways of joining up and combining the conductors on the armatures of dynamos. Workshop details concerning materials and modes of construction are considered in Chapter XIII.

It has been pointed out, on p. 39, that continuous-current dynamos are usually provided with closed-coil armatures, that is to say armatures on which, whether wound according to the ring, drum, or disk type, the winding is re-entrant on itself, the current dividing between at least two paths and re-uniting as it leaves the armature. For machines with two poles there are but two such paths, the current dividing once only. But for multipolar machines there may be either two, or more than two, such paths; with one, or more than one, bifurcation of the current. The electromotive-force of the machine will obviously depend on the mode of connection of the conductors as to how many active conductors are connected in series. Hence the necessity of understanding the theory of armature winding.

To connect uprightly the conductors on an armature so as to produce the desired result is a simple matter in the case of ring-winding, for continuous-current machines, whether of bipolar or multipolar type. It is a much less easy matter in the case of drum-windings, especially, for multipolar machines. Often there are several alternative ways of arriving at the same result; and the fact that methods which are electrically equivalent may be geometrically and mechanically different makes it desirable to have a systematic method of treating the subject.

In Chapter III., pp. 36 to 44, we have already considered

the elementary structure of ring, drum and disk armatures. Those elements would suffice for the consideration of small armatures coiled with only a few turns of wire. But when we proceed to the design of large machines, or of machines which are to be wound so as to give potentials as high as 400 or more volts, further information is needed. For example, suppose we have designed a 4-pole machine having a bar-armature with 100 bars spaced around its periphery, all in one layer, numbered consecutively from 1 to 100, and we desire to complete the end-connections; we must be able to instruct the workman as to the order in which they are to be connected. Is he to connect the front¹ end of bar No 1 right across to bar No. 50, or No. 49? Or is he to connect it across a quarter of the periphery, and, if so, is it to join No. 25 or No. 24, or to No. 75 or No. 76? To which return-bar is he to connect the back end of the bar? And which bars are to be connected down to the commutator?

The object of the present chapter is to give information on these points. Brevity is essential; and much more might have been written. Those who wish to go further should consult the writings of Hering,² Arnoux,³ Fritsche,⁴ Weymouth,⁵ Arnold,⁶ Parshall and Hobart,⁷ as well as sundry specifications to which reference will be made.

As remarked above, there is generally little trouble in understanding a ring winding, provided the distinction between a right-handed and a left-handed winding is comprehended.

Fig. 160 shows one section of a ring, the direction of the currents being indicated in the same way as on p. 72, Figs. 60 to 62. As we pass right-handed around the circle from *a* to *b* we follow a right-handed spiral path, the current climbing

¹ "Front" end means the end where the commutator is; armatures being always most conveniently regarded from this end.

² Herring: *Principles of Dynamo-Electric Machines*, New York, 1891.

³ Arnoux: *L'Electricien*, xii. 737, 774, 827, 1888.

⁴ Fritsche: *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

⁵ Weymouth: *Drum Armatures and Commutators*, London, 1893.

⁶ Arnold: *Die Ankerwicklung der Dynamomaschinen*, Berlin, 1891.

⁷ Parshall and Hobart: *Armature Windings of Electric Machines*, New York, 1895.

(as explained on p. 60) to the positive brush at the top. (A left-handed coiling, such as Fig. 31, p. 38, would give the positive brush at the bottom, unless either the rotation or the polarity of the dynamo were reversed.) To say whether a drum armature is right-handedly or left-handedly wound we must first settle upon the particular end of it from the point of view of which our statement is to be applicable; for instance the commutator end is conveniently taken as the one at which we are supposed to be looking. And we must also fix upon a certain sense of rotation (say clockwise) in which we intend to take the order of the commutator bars. These two matters being fixed arbitrarily, then a right-handed winding may be

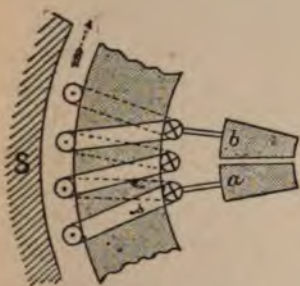


FIG. 160.—RIGHT-HANDED
RING-WINDING.

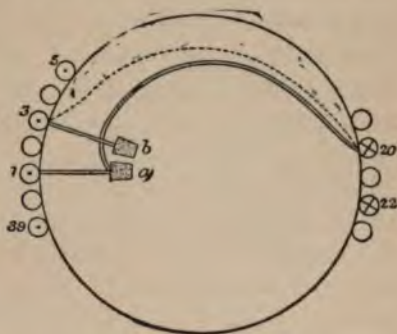


FIG. 161.—RIGHT-HANDED
DRUM-WINDING.

defined as follows. That winding is right-handed which in leading from one bar to the next (in the order fixed as above) forms a right-handed screw. Now consider Fig. 161, which depicts one element or section of a drum-winding having 40 external conductors. Starting from *a* to climb to *b*, and noting the direction of the currents in the conductors, it is obvious that *a* must be connected by a spiral connector across the front end of the drum to one of the descending conductors such as No. 20, from which at the back end another connector must join it to one of the ascending conductors, such as No. 3, where it is led to *b*, thus making one right-handed turn. Now examine Fig. 173, p. 259, and Fig. 178, p. 263. They are both

left-handed, the latter having eight turns of wire in one section. Note in passing that if the back connector in Fig. 161 from No. 20 to No. 3 had passed under the shaft, instead of over it, the winding would still have been a right-handed winding.

The next point is to ascertain over how many conductors these spiral connectors ought to pass. We connected No. 1 (*vid* the bar *a*) to No. 20, and then back to No. 3. Is there any reason why No. 20 should have been chosen and not No. 21, or No. 19, or No. 18. To understand this we must consider the question of commutation in the conductors as a whole, and also remember that there are two paths through the windings from brush to brush. This is a drum with 40 conductors in one layer: and there will be 20 bars in the commutator. Remember that the induced electromotive-forces will be directed from back to front in the conductors rising on the left, and from front to back in those descending on the right. It is natural to think that each conductor ought to be joined to the one that lies diametrically opposite to it. In that case No. 1 should be joined to No. 21, No. 2 to No. 22, and so forth. But this will not do. Each conductor on one side needs a return conductor on the other side. The even numbers may be looked upon as the returns for the odd numbers. Hence No. 1 ought not to be joined to No. 21. Shall it be joined to No. 20 or to No. 22? or shall we join it to No. 18? Nos. 20 and 22 lie on either side of the one that is diametrically opposite, and electrically it makes no difference which we select of these two. If we are going to use a back connector which returns over the shaft (as in Fig. 161), there is a slight saving of copper if we select No. 20. If the back connector returns under the shaft, either may be taken. More copper will be saved if we select No. 18 and return over the shaft, as the spiral connectors will be shorter. But if we thus connect across a short chord of the circumference, instead of taking the chord nearest to the diameter, we risk getting counter electromotive-forces in the turns that are in series from brush to brush. On the other hand, as Swinburne has shown, connecting across a short chord has the advantage that the armature has a smaller demagnetizing action. The

effect of winding across a chord subtending the span of the pole-piece is shown by Fig. 162, in which it will be seen the belt of demagnetizing conductors between the pole tips is now replaced by a belt, in which the currents flow in two opposing directions, thus neutralizing one another. In no case should the chord subtend a less angle than that subtended by the polar face. The rule then for connecting is as follows for a simple 2-pole drum armature. The number of conductors Z being an even number, the front connector must cross from any conductor to that which is $\frac{1}{2} Z \pm 1$ further on (or $\frac{1}{2} Z \pm 3$ for shortening the chord); and the back connector must lead back to the next conductor but one. In the following winding-table the letters F and B stand for *front* and *back*, and the

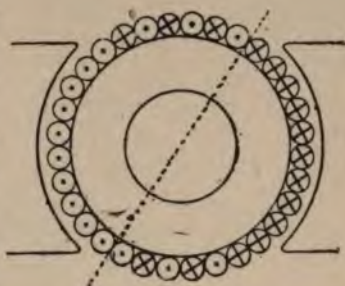


FIG. 162.—EFFECT OF CHORD-WINDING.

WINDING-TABLE. 2-POLE DRUM. 40. CONDUCTORS.

F	B	F	B	F	B	F	B	F
D	U	D	U	D	U	D	U	
1	22	3	24	5	26	7	28	
9	30	11	32	13	34	15	36	
17	38	19	40	21	2	23	4	
25	6	27	8	29	10	31	12	
33	14	35	16	37	18	39	20	

letters U and D stand for *up* and *down*, meaning toward the front end, and from the front end respectively. From this it will be seen that starting with conductor No. 1, we follow *down* it to the back, there connect it to No. 22, then come *up* to the *front*, then come (connecting to a bar of the commutator in passing) to No. 3, go down this, and connect across the

back to No. 24, and so on. The overlap is in this case + 21 at the back end, and — 19 at the front end. At last we come to No. 20, up which we return to the front and connect to No. 1, taking the last bar of the commutator on the way.

Simple as the matter may seem, the problem how to connect across the end of the drum from one conductor to that which is next but one, or next but three, to the diametrically opposite conductor, is not altogether easy when the mechanical and electrical difficulties are taken into account. To shorten the length of the long spiral connectors, and make the end-connections more symmetrical, the arrangement indicated in Fig. 163 is now often used. The spirals are thus

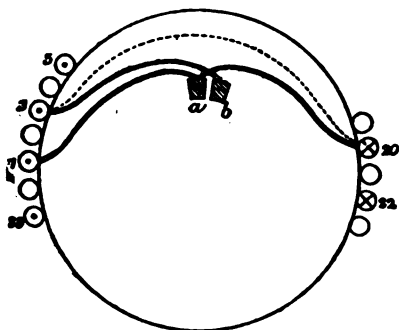


FIG. 163.—DRUM-WINDING WITH TWO SETS OF SPIRAL CONNECTORS.

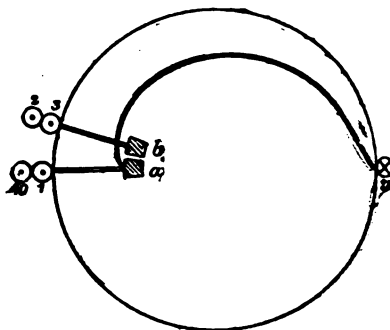


FIG. 164.—TWO-LAYER DRUM-WINDING.

arranged in two layers one over the other, as in Figs. 231 and Plate IV., with the effect that the commutator has virtually been turned through about a quadrant, so that the + brush will be on the left instead of at the top. It has the advantage that all the spiral connectors at either end may be made of the same size.

If, however, the conductors are arranged in two layers one over the other, the windings may be made across a diameter, the last turn being brought across to the next in the same layer. The conductors of the outer layer then answer instead of the intermediate members of the one-layer set. In Fig. 164 the end of No. 1 is brought to a

thence it spirals round to No. 21, which is connected across the back to No. 3, and so on. Fig. 165 shows how the 80

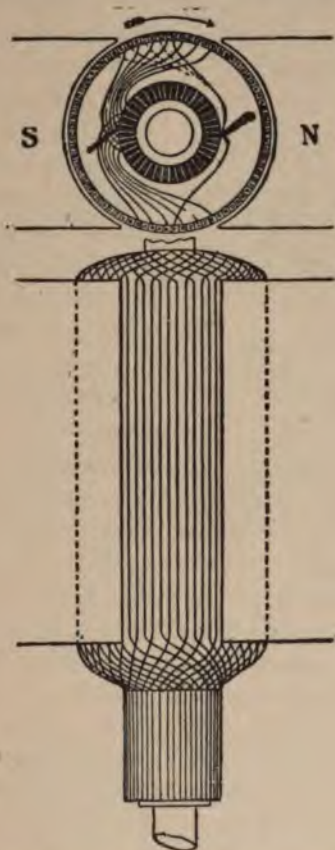


FIG. 165.—DRUM-WINDING OF EDISON-HOPKINSON DYNAMO.

conductors of the wire-wound Edison-Hopkinson armature (see p. 353) are connected, there being in reality two layers of 40 each, and a 40-part commutator.

DEVELOPED WINDING DIAGRAMS.

There is a great advantage in adopting a mode of representation (originally suggested by Fritsche of Berlin) in

which the armature winding is considered as though the entire structure had been developed out on a flat surface.

Consider first Fig. 166, which is a partial sketch of a four-pole machine laid on its side. The core, which may be hereafter wound either as ring or as drum, lies between the four poles of alternate polarity. If a

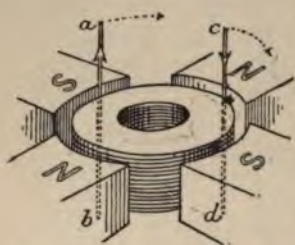


FIG. 166.—SKETCH OF 4-POLE FIELD.

copper rod *a* is placed parallel to the axis to represent one of the armature conductors, and is supposed to move along the gap-space right-handedly past the S pole, it will cut the magnetic lines entering that pole. By the rule given on p. 22, the induced electromotive-force in it will be upwards. Another conductor *c* passing the N

pole will have induced in it a downward electromotive-force. If one were to attempt in a picture such as this to show twenty or more conductors and their respective connections, the drawing would be unintelligible. Accordingly we have to imagine ourselves placed at the centre, and the panorama of the four poles around us to be then laid out flat, as in Fig. 167. It will be noticed that the faces of the N and S poles are shaded obliquely for distinction.¹

Now in an actual machine there are many armature conductors spaced symmetrically around, and these have to be grouped together by connecting wires. In the case of ring windings the wires which connect the active conductors in the gap-space pass through the central aperture in the ring when they are removed from the magnetic field. Suppose, for simplicity, we have a ring armature of only 12 turns, and 12 bars to the commutator. If this is opened out from the

¹ I choose these oblique lines for the following reason. If instead of the line *a b* (representing a conductor), a narrow slit in a piece of paper were laid over the drawing of the pole-face, and moved as the dotted arrows show towards the right, the slit in passing over the oblique lines will cause an apparent motion in the direction in which the current tends in reality to flow. It is easy to remember which way the oblique lines must slope; for those on a N pole-face slope parallel to the oblique bar of the letter N.

inside we shall have the form shown in Fig. 168 where the dotted lines are the inactive parts of the spiral winding that pass through the inside of the ring. By tracing the arrows it

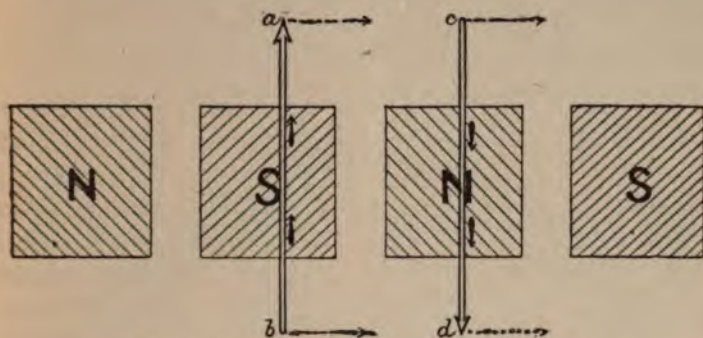


FIG. 167.—4-POLE FIELD DEVELOPED FLAT.

will be seen that there must be two positive and two negative brushes. Fig. 169 gives an end-view diagram of the same winding, by which the two modes of presentation may be

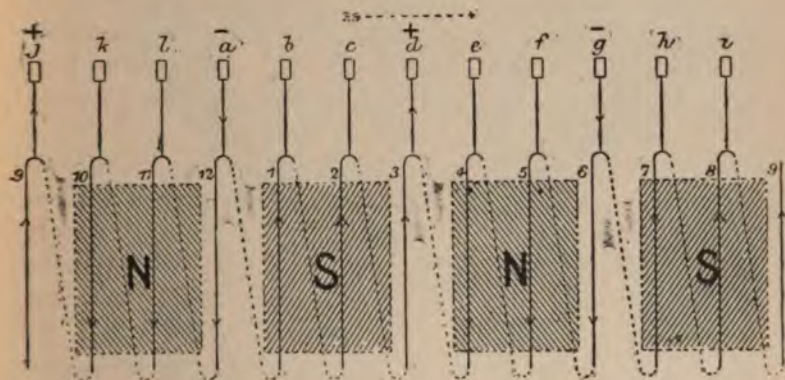


FIG. 168.—DEVELOPMENT OF RING-WINDING FOR 4-POLE MACHINE.

compared. It is clear that in this case the armature might be used as two separate machines to furnish two separate currents, though this would not be desirable. It is usual to

couple the positive brushes together, and the negative brushes together. A 6-pole machine would require six brushes, and so forth. The reader should examine the cuts of the Berlin dynamos, Plate VIII. When the brushes of the same sign are thus connected together the electromotive-force of the whole armature is simply that of any of the sets of coils from one + brush to the adjacent — brush. In this 4-pole machine the

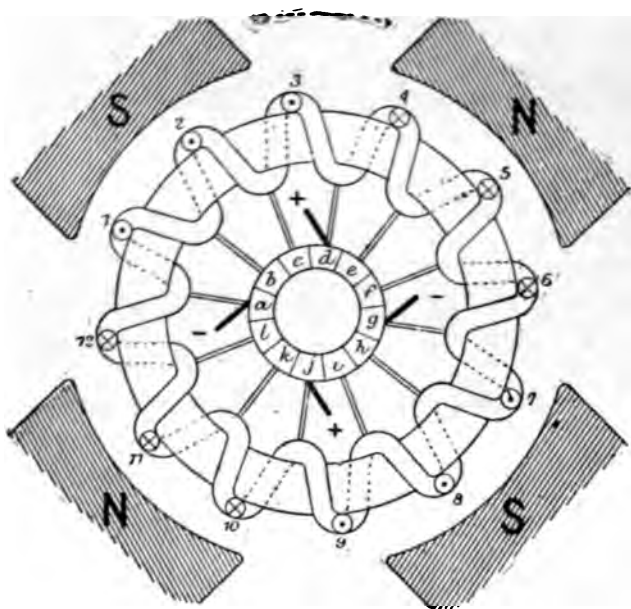


FIG. 169.—RING-WINDING FOR 4-POLE MACHINE
(CORRESPONDING TO FIG. 168).

coils of the four quadrants are in four parallels; the internal resistance is one-sixteenth of the total resistance around the entire ring. There is, as we shall see, another mode of connecting the coils of a multipolar ring, in which the quadrants, instead of being all in parallel, are in series, so as to give two parallels only. This mode is sometimes called *multipolar series*, or *single circuit winding*; it would be more properly called *series-grouping*. It requires only two

sets of brushes at neutral points on the commutator, however many poles there are around the ring.

In further applying the method of development to those cases in which the winding is entirely exterior to the core, as

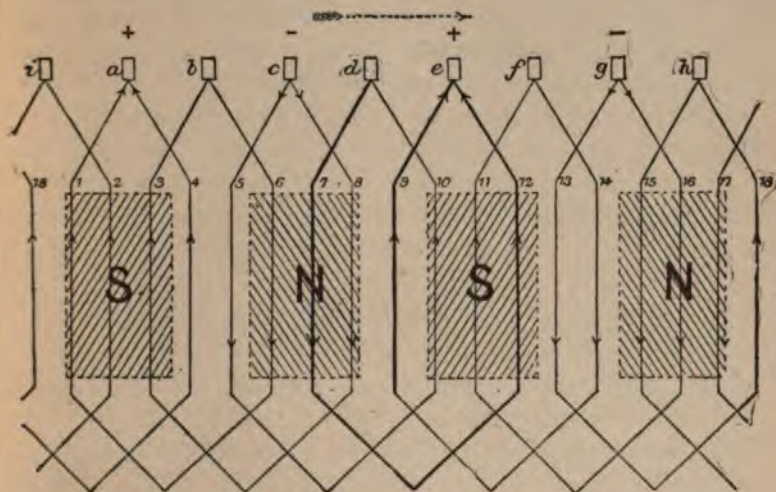


FIG. 170.—TYPICAL LAP-WINDING.

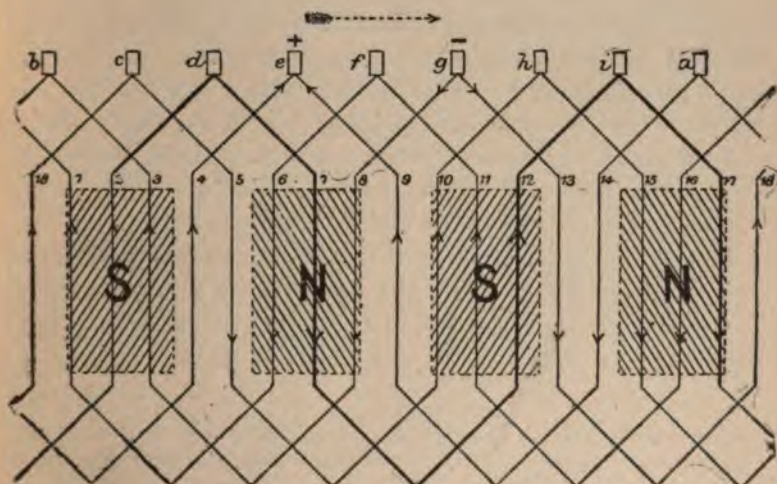


FIG. 171.—TYPICAL WAVE-WINDING.

for drum armatures, or to those in which there is no core at all, namely for disk armatures, we find that there are two distinct modes of procedure, which we may respectively denote¹ as *lap-winding* and *wave-winding*. The distinction arises in the following manner. Since the conductors that are passing a north pole generate electromotive-forces in one direction, and those that are passing a south pole generate electromotive-forces in the opposite direction, it is clear that a conductor in one of these groups ought to be connected to one in nearly a corresponding position in the other group, so that the current may flow down one and up the other in agreement with the directions of the electromotive-forces. If now we examine Fig. 170 we shall see that at the back of the armature (or end distant from the commutator) each conductor is united to one five places further on—No. 1 to No. 6, No. 3 to No. 8—and that at the front end the winding, after having made one “element” (as for example *d-7-12-e*), then forms a second element (*e-9-14-f*), which laps over the first; and so on all the way round until the winding returns on itself.

Now contrast with this Fig. 171, in which, though the connections at the back end are the same, those at the commutator end are different. It will be seen that when the winding returns back toward the commutator, instead of lapping back toward the part from which it started, it is turned the other way. The winding *d-7-12* does not return at once to *e*, but goes on to *i*, whence another element *i-17-4-e* goes on in a sort of zig-zag wave. These are both drum windings, the corresponding tables being as follows:—

It will be noted in passing that whilst with this particular number of conductors (18) the lap-winding results in four parallels of coils, and needs four brushes, the wave-winding results in two parallels, and requires two brushes only.

¹ The wave-winding is Fritsche's *Wellen-wicklung*; the lap-winding is called by Arnold (*op. cit.*) *Scheitel-wicklung*. Wave-windings were early used by Matthews, Bollmann, and Müller; and by Ferranti and Lord Kelvin in alternate-current generators.

WINDING-TABLE FOR FIG. 170.
(LAP-WINDING.)

F		B		F
$+a$	1	6		b
b	3	8		c
$-c$	5	10		d
d	7	12		e
$+e$	9	14		f
f	11	16		g
$-g$	13	18		h
h	15	2		i
i	17	4		a

WINDING-TABLE FOR FIG. 171.
(WAVE-WINDING.)

F		B		F
a	1	6		f
f	11	16		b
b	3	8		g
$-g$	13	18		c
c	5	10		h
h	15	2		d
d	7	12		i
i	17	4		e
$+e$	9	14		a

WINDING FORMULÆ FOR CLOSED COIL ARMATURES.

General formulæ for connecting—applicable chiefly to drum-windings—have been given by Hopkinson, by Müller and by Arnold. We shall follow the latter in the main. There is no difficulty about ring-windings; but a few special cases are separately considered later. With drum-windings, however, certain complications arise needing discrimination.

In deducing a formula for finding the proper spacing of conductors in a drum armature, it is well to begin with a bipolar machine, and then afterwards consider the effect of having more than two poles. We have seen from Fig. 161 that it is desirable in order to obtain a symmetrical winding to set aside the even numbers as returns for the odd numbers. Now in Fig. 161 there is only one spiral around the armature in passing from the bar a to the bar b , but in a high-voltage machine there might be several spirals. However many there may be, we will call this portion of the winding that lies between two commutator bars an "element" of the winding. Suppose it consisted of five spirals, then there would be ten conductors in one element, that is to say, five conductors together in a group at one side of the

plex windings out of account, for the sake of simplicity, a will be the number of bifurcations of the current through sets of coils that are in parallel with one another.

The number of neutral points on the commutator will be always $= 2a$. The number y must always be, relatively to s , a prime number, otherwise the winding will not be re-entrant as a closed coil. If they have a common factor (as, for example, $s = 36$, $y = 27$, where the common factor is 3) there will be as many *independent* circuits. In applying the formulæ we have several cases to deal with.

(i.) *Parallel Grouping.* We have seen in the case of an ordinary ring that there will, in a 4-pole field, be four rows of $\frac{1}{2} Z$ coils each in parallel with one another. Any grouping which results in as many rows in parallel as there are poles around the armature is called a *parallel grouping*. In a 12-pole field we should have 12 rows of $\frac{1}{12} Z$ each, in parallel. Each pair of such rows may be considered as constituting a separate 2-pole armature. It is also so for drum armatures if wound with lap-windings, but not if with wave-windings. The two cases stand thus for getting a parallel grouping:—

- (a) *With Lap-winding* write in the formula $p = 1$ and $a = 1$, and apply it to a set of conductors lying between two poles of similar name.
- (b) *With Wave-winding* write $a = p$; that is to say, there must be as many bifurcations of the current as there are pairs of poles. In a 6-pole machine $p = 3$, and the current will bifurcate at three points (the three negative brushes), going through six parallel paths to the three positive brushes (or to the cross connections that lead to the positive brush).

(ii.) *Series Grouping.* For this, seeing that the current only bifurcates once, $a = 1$, whatever the mode of coiling. In the case of 2-pole machines the series grouping and parallel grouping are the same thing—there are two rows of coils in parallel with one another, and the winding may be either a wave-winding or a lap-winding. For 4-pole machines

the same holds good. For machines having more poles than four, however, the only possible cases of series grouping are wave-windings.

(iii.) *Mixed Groupings.* There are several possible cases of mixed lap- and wave-windings, corresponding to cases where $a > 1$ or $a > p$.

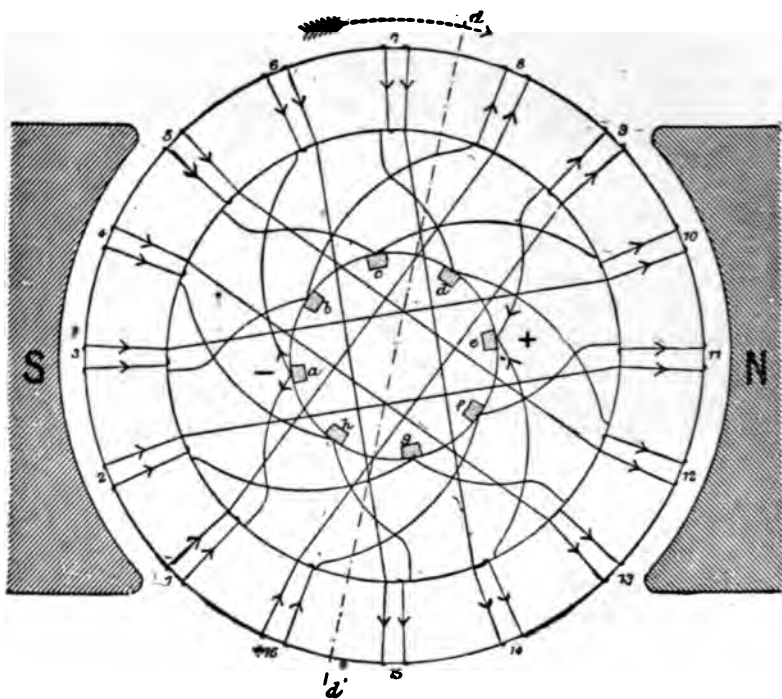


FIG. 172.—RING-WINDING WITH OPPOSITE COILS IN SERIES.

As examples for verifying these formulæ we may take the following :

In the ring-winding, Fig. 34, p. 40, $Z = 32$; $p = 1$; $b = 4$; $s = 8$; $c = 8$. Hence $y = 7$ or 9 . But the ring has eight sections only, of which, therefore, the seventh and the ninth, reckoned from any given section, are those that lie on either side of it.

In the drum-winding, Fig. 69, p. 85, $Z = 32$; $p = 1$; $b = 2$ (because each "element" of the winding from bar to bar of the commutator contains two active conductors); $s = 16$; $c = 16$. Hence $y = 15$ or 17 . The former number may be taken as referring to the front layer of connections (No. 1 to No. 16), the latter to the layer below them (No. 2 to No. 19).

A further example is afforded by a special ring-winding used by Wodicka, Fig. 172, in which each section is joined in series with one on the side opposite to it, so that the number of commutator bars is half that of the sections. Here each "element" of the winding consists of two sections each containing active conductors; hence $b = 4$; $Z = 32$; $s = 16$; $p = 1$; whence y may be either 9 or 7.

DRUM-WINDINGS.

In Fig. 173 is given a drawing of drum-winding applied to an 8-part armature. As in all Siemen's earlier drums the windings lay in two layers, each section being wound diametrically. Thus starting from the bar of the commutator

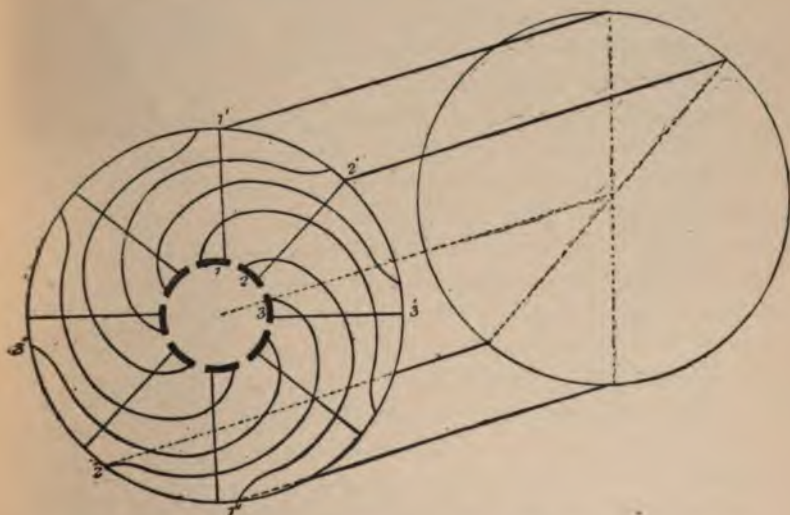


FIG. 173.—CONNECTIONS OF SIEMENS (VON HEFNER-ALTENECK) WINDING.

marked 1 we pass outwards to 1', then down the armature, across the back, up to 1'', and (after having wound a sufficient number of turns to form a section) spiral up to bar 2 of

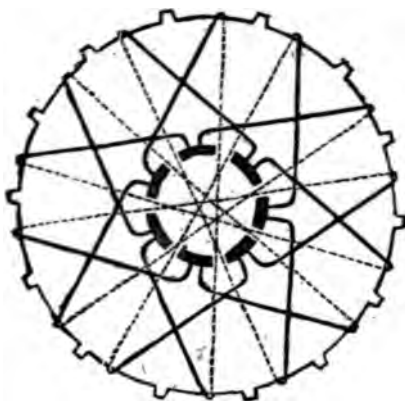


FIG. 174.—CONNECTIONS OF
EDISON WINDING.

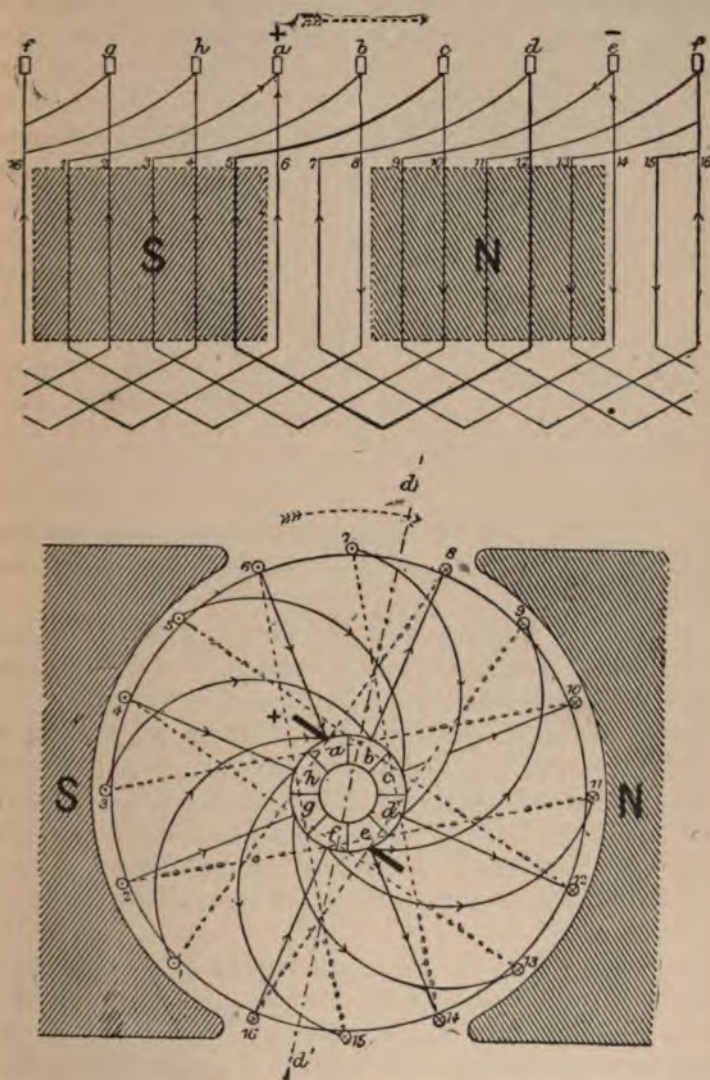
the commutator. The Edison variety of Siemens' winding is shown in Fig. 174. The diagram only shows a simple case with a 7-part commutator. Here $S = 14$; $b = 2$; and according to the formula y should be 6. But the actual value of the spacing is 7 at the back and 5 at the front end, as will be seen. With an odd number of sections commutation does not occur simultaneously (in bipolar machines)

at both the brushes, but alternately.

A closer study of the drum-winding is important, and accordingly there are given a series of winding diagrams relating to several varieties.

In Figs. 175 and 176 are given a right-handed winding on Siemens' plan for an 8-part commutator, and one turn to each section, *i. e.* with 16 conductors spaced round the periphery. The connecting pieces at the front end consist of straight connectors (such as a 6) and spiral connectors (such as a 1), which cross (either under or over) the former. The connecting pieces at the back end are not further indicated than by the dotted lines drawn across. In the developed diagram it is shown that each element of the winding is similar to $c-5-12-d$ and that the arrangement is a lap-winding. The back connectors space over seven conductors, being just short by one of the number $\frac{1}{2} Z$ in the semi-circumference; whilst the front connectors space over five, being short by three of the semi-circumference. It will be further noted that with this right-

handed winding, rotating right-handedly in a right-handed field, the + brush is near the top of the commutator.



FIGS. 175 and 176.—LAP-WINDING (SIEMENS' RIGHT-HANDED) DEVELOPMENT AND END VIEW.

Figs. 177 and 178 represent the same thing, except that the winding is left-handed, with the result that the + brush is now near the bottom of the commutator.

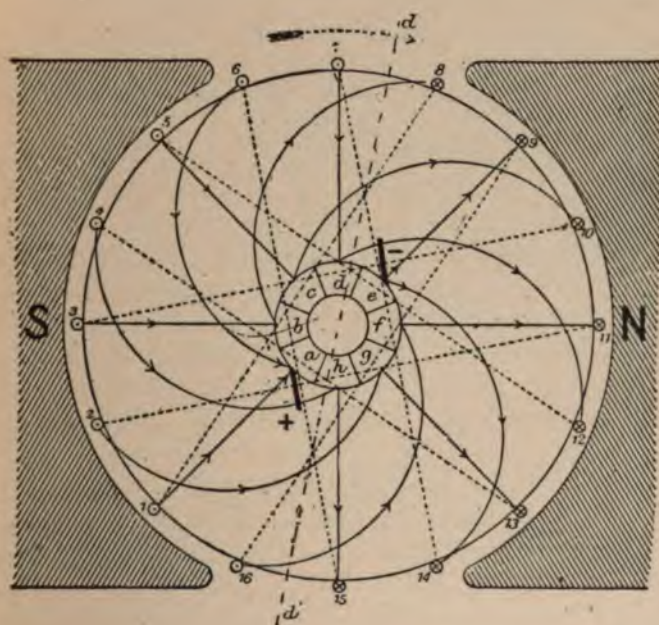
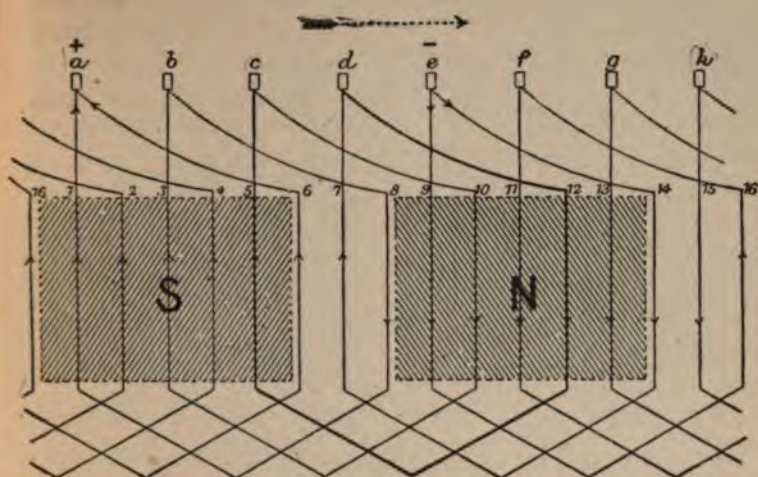
The winding table for both these figures is the same, namely :—

F		B		F
+ a	1	8		b
b	3	10		c
c	5	12		d
d	7	14		e
— e	9	16		f
f	11	2		g
g	13	4		h
h	15	6		a

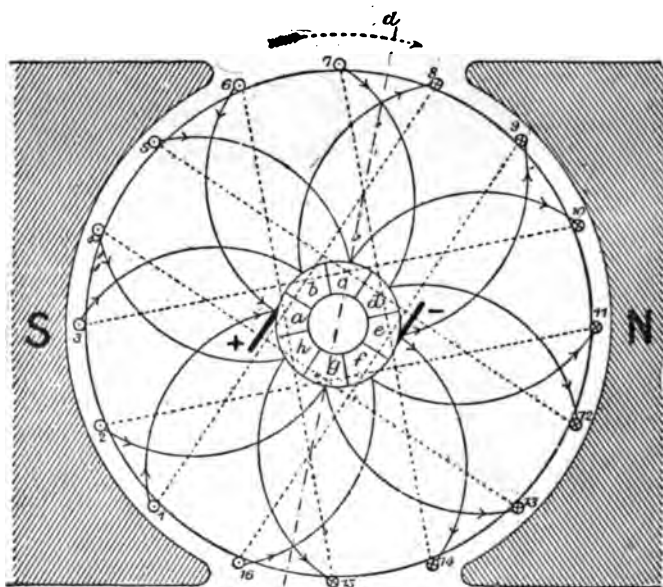
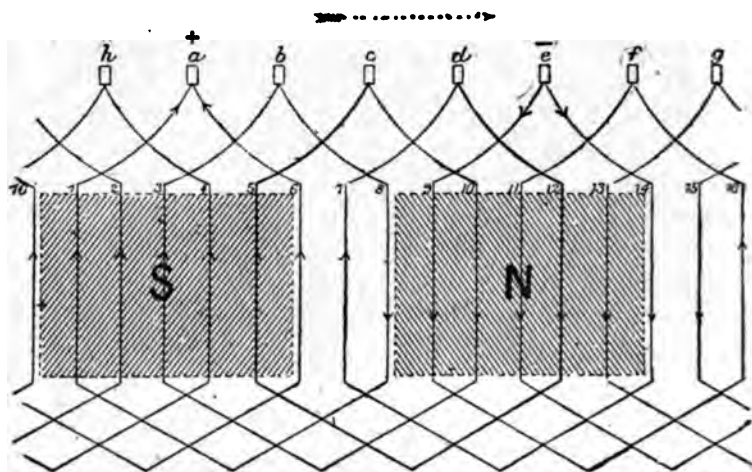
But in the right-handed winding the spiral connectors, such as *a* to 1, go toward the left, and in the left-handed winding to the right.

In Fig. 175 and Fig. 177 (the developments) it is seen that for both these windings the “element” of the winding, indicated by the darker lines, is unsymmetrical at the front connectors, one straight, one spiral. The bar *a* of the end of the drum, this being due to the use of two sorts of commutator is connected to the front end of conductors No. 1 and No. 6. In one case it is skewed forward to be opposite No. 6; in the other it is skewed backward to be opposite No. 1. Why should it not be placed symmetrically between them?

Figs. 179 and 180 depict a symmetrical lap-winding, electrically precisely equivalent to the preceding, and having the same winding table. The advantages are twofold: that (for built-up armatures) the connectors at the front end are now 1 of the same pattern, consisting of two sets of short spirals; and that the brushes now come to a horizontal diameter where they are more accessible. The back connections remain



FIGS. 177 and 178.—LAP-WINDING (SIEMENS' LEFT-HANDED) DEVELOPMENT AND END VIEW.



FIGS. 179 AND 180.—LAP-WINDING (2-POLE SYMMETRICAL DEVELOPMENT AND END VIEW.

exactly as before, and go across a longer chord than the front connections.

To secure the utmost symmetry in the winding, the back and front connectors ought to be equalized. The theoretically proper spacing is $y = 7$ or $y = 9$. To attain this, join No. 1 to No. 8 at one end of the drum and to No. 10 at the other. The result is shown in Figs. 181 and 182, from which it is at once apparent that we have passed from lap-windings to a wave-winding; each element passing around the drum and returning only to the next bar of the commutator from whence it started. The winding-table for this case is:—

F		B		F
$+ a$	16	9		b
b	2	11		c
c	4	13		d
d	6	15		e
$- e$	8	1		f
f	10	3		g
g	12	5		h
h	14	7		a

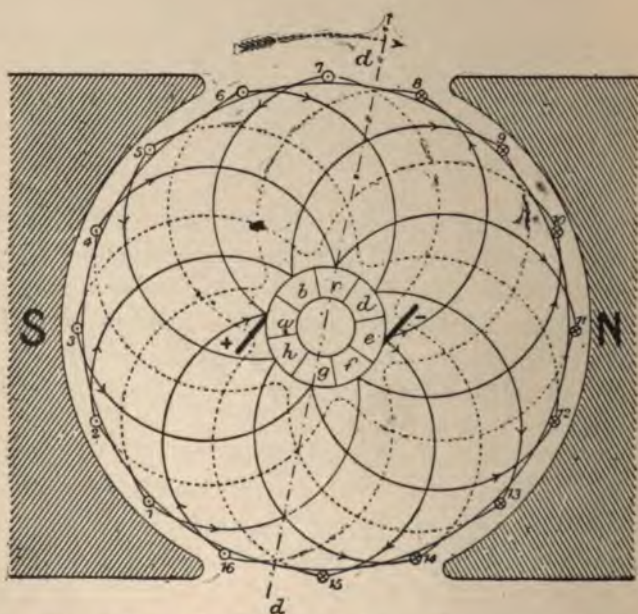
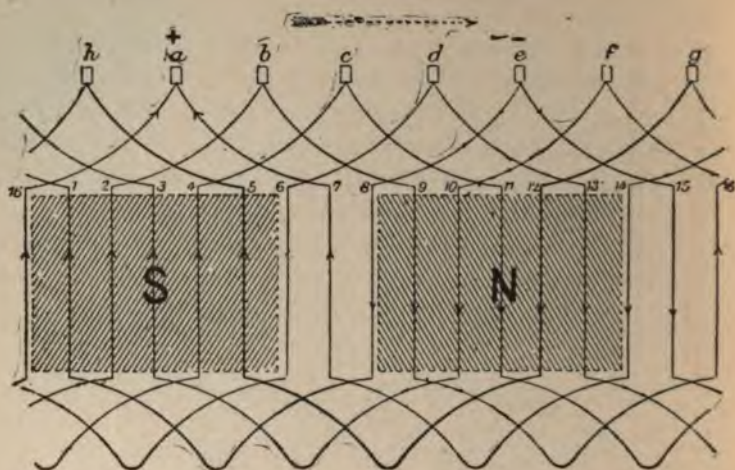
Electrically this winding is the precise equivalent of the three preceding. The spiral connectors at the back end meet in pairs as those at the front meet at the commutator.

A two-layer winding for twenty-four conductors, together with its development, are given in Figs. 183 and 184, showing how, when half the armature, from a to g , has been completed one layer has been wound.

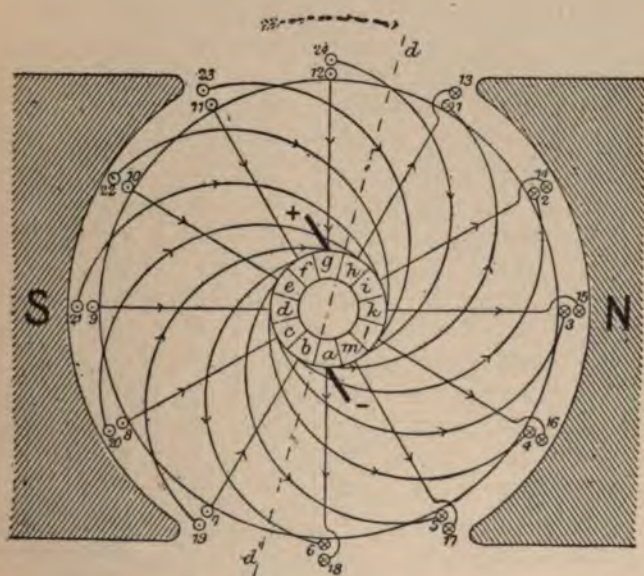
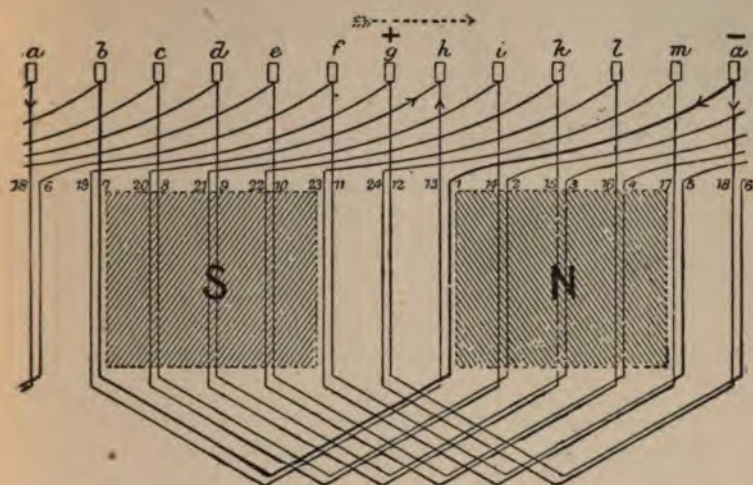
Multipolar Drums.—As mentioned on p. 278 below, the winding of multipolar armatures with series-grouping was suggested by Professor Perry.¹ It has been applied to drum-winding by Messrs. Paris and Scott,² and by Mr. Kapp. For the case of multipolar machines it is convenient to state the

¹ Specification of Patent, No. 3036 of 1882.

² Specification of Patent, No. 4683 of 1884.



FIGS. 181 and 182.—WAVE-WINDING (2-POLE SYMMETRICAL) DEVELOPMENT AND END VIEW.



FIGS. 183 and 184.—TWO-LAYER DRUM-WINDING.

rule in words that if a series grouping (so as to give high voltage) is desired, y must be an odd number and that the total number of conductors must be equal to y times the whole number of poles, plus or minus two. For example; for a 6-pole drum, taking y as 15, the number of conductors must

WINDING TABLE FOR 6-POLE DRUM ARMATURE; 202 CONDUCTORS;
SERIES GROUPING: BRUSHES (+) 135° APART.

F	B	F	B	F	B	F	B	F
D	U	D	U	D	U	D	U	
202	25	50	75	100	125	150	175	
200	23	48	73	98	123	148	173	
198	21	46	71	96	121	146	171	
196	19	44	69	94	119	144	169	
194	17	42	67	92	117	142	167	
192	15	40	65	90	115	140	165	
190	13	38	63	88	113	138	163	
180	11	36	61	86	111	136	161	
186	9	34	59	84	109	134	159	
184	7	32	57	82	107	132	157	
182	5	30	55	80	105	130	155	
180	3	28	53	78	103	128	153	
178	1	26	51	76	101	126	151	
176	201	24	49	74	99	124	149	
174	199	22	47	72	97	122	147	
172	197	20	45	70	95 +	120	145	
170	195	18	43	68	93	118	143	
168	193	16	41	66	91	116	141	
166	191	14	39	64	89	114	139	
164	189	12	37	62	87	112	137	
162	187	10	35	60	85	110	135	
160	185	8	33	58	83	108	133	
158	183	6	31	56	81	106	131	
156	181	4	29	54	79	104	129	
154	179	2	27	52	77	102	127	
152	177	202						

be either 88 or 92; not 90. On p. 268 is given a winding-table, calculated by Mr. Kapp for an 8-pole machine having a spacing of $y = 25$.

It may be remarked in passing that if in multipolar machines the number of sections is an exact multiple odd or even of p , the grouping will be parallel: and if it is an odd multiple then commutation will not occur simultaneously at all the brushes, but alternately at all the + brushes and at all the — brushes, similarly to the alternate commutation in a 2-pole machine when there is an odd number of sections in the winding.

In Fig. 185 and 186 are given the connections for a 4-pole drum-winding with twenty-two conductors; here $y = 5$. The winding-table for this armature is as follows:—

4-POLE DRUM : 22 CONDUCTORS : SERIES GROUPING.

F	B	F	B	F
D	U	D	U	
1	18	13	8	
3	20	15	10	
5	22	17	12 +	
+ 7	2	19	14	
9	4	21	16	
11	6	— 1		

In Fig. 187 and 188 is given a lap-winding used by Thury (see Fig. 297, p. 442), the case illustrated being that of a 4-pole drum. It is a lap-winding for parallel grouping, with a spacing at the back end just short of the pitch of the poles and a still shorter spacing at the front end. This is a form of chord winding intended to keep conductors at very different potentials from overlapping, and it can be well insulated because the separate sections can be wound on formers before being laid over the core.

FIG. 107.

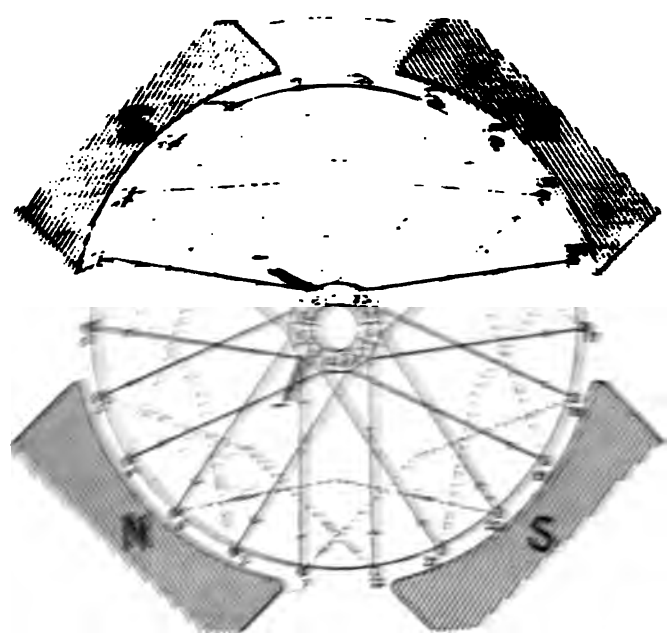
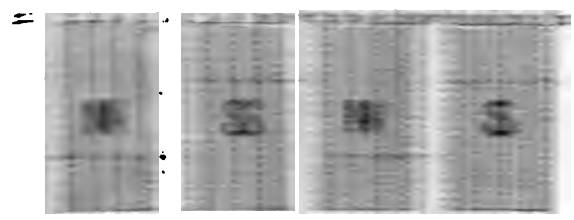
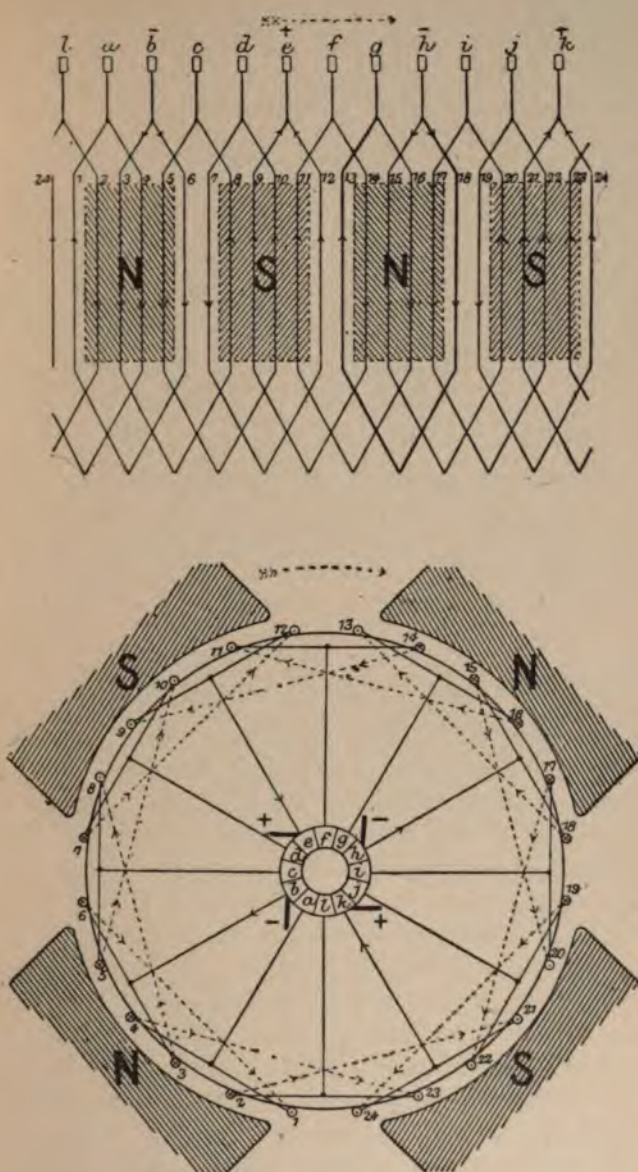


FIG. 107 and 108.—MULTIPOLAR DRUM-WINDING: SERIES GROUPING.



FIGS. 187 and 188.—THURY'S ARMATURE (4-POLE LAP-WINDING.)

A method of drum-winding was proposed by Fritsche,¹ in which the conductors all lie obliquely across the surface of the drum, no part of them being parallel to the shaft. In this case the field-magnet poles are also constructed with diagonal

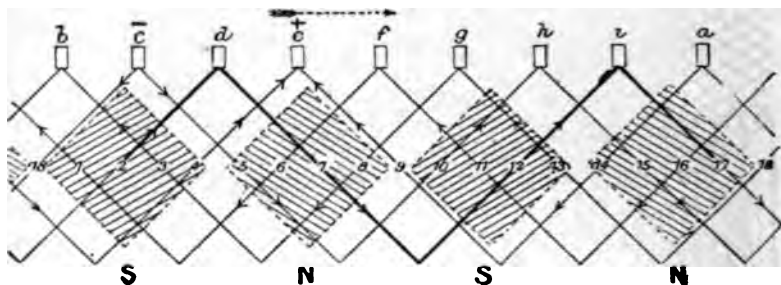


FIG. 189.—FRITSCHÉ'S OBLIQUE WAVE-WINDING.

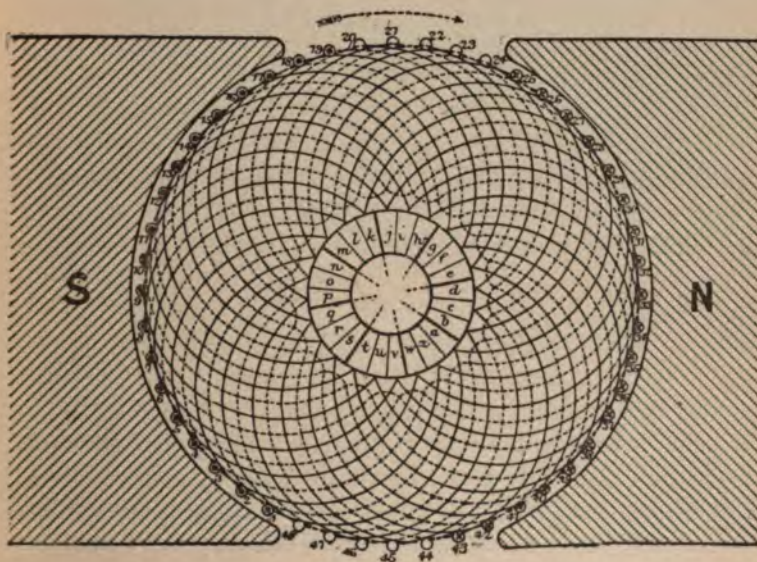
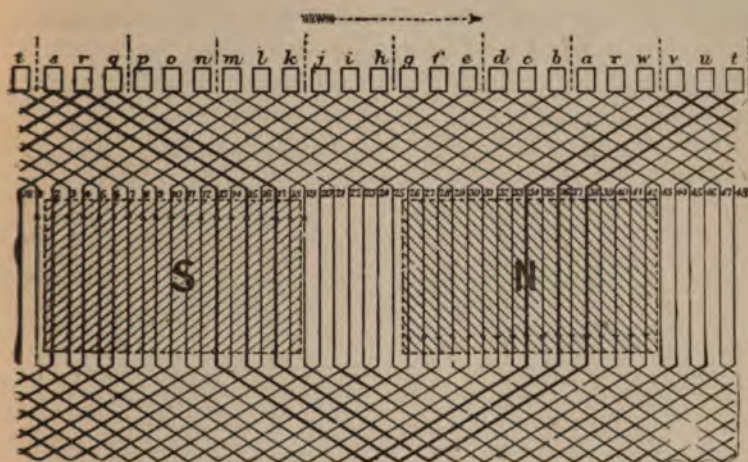
faces. This oblique winding is shown developed in Fig. 189; which should be compared with the winding of Fig. 201, to which it is electrically equivalent.

MULTIPLEX WINDINGS.

In dynamos intended to yield currents so large that a difficulty in commutation is likely to arise, it is convenient to have two or more distinct windings on the armature, each connected to its own set of commutator bars, all the sets being interleaved in one commutator. The current in such cases is collected by a pair of brushes broad enough to make contact over two or three consecutive bars, or by a set of several brushes connected in parallel so as to virtually form broad brushes. The advantage of duplex or triplex windings having two or three independent circuits is that only a fraction of the whole current has to be reversed in the passing of any one bar of the commutator. The division of what would otherwise be very stout conductors into several smaller conductors, also has the effect of reducing eddy-current loss

¹*Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

Figs. 190 and 191 show the connections of a triplex-wound drum-armature for a 2-pole field having 48 conductors in



FIGS. 190 and 191.—TRIPLEX-WOUND 2-POLE DRUM ARMATURE.

all, that is to say, 16 in each independent circuit. In practice a greater number of conductors would of course be used. Each circuit is wound as an ordinary drum-winding, being connected to 8 bars of the commutator. There are no connections between the three circuits except such as are made by the brushes, which are broad enough to overlap three bars of the commutator, thus putting the three circuits in parallel.

The winding-tables for this armature are as follows :—

CIRCUIT a.				CIRCUIT b.				CIRCUIT c.			
F	B	F		F	B	F		F	B	F	
a	1	22	d	b	47	20	e	c	45	18	f
d	43	16	g	e	41	14	h	f	39	12	i
g	37	10	j	h	35	8	k	i	33	6	l
j	31	4	m	k	29	2	n	l	27	48	o
m	25	46	p	n	23	44	q	o	21	42	r
p	19	40	s	q	17	38	t	r	15	36	u
s	13	34	v	t	11	32	w	u	9	30	x
v	7	28	a	w	5	26	b	x	3	24	c

Fig. 192 shows the connections of a triplex-wound drum-armature for a 4-pole field. The connections are sufficiently clear without the aid of a winding-table. There are 90 conductors, 30 in each circuit, the spacing being 21.

MULTIPOLAR RING-WINDINGS.

Of these something has been already said on p. 250. It was noted that an ordinary ring placed in a multipolar field would have as many neutral points on its commutator as there are poles around it, and would therefore need as many brushes as the machine had poles. In plate VIII. are given two views of the large Berlin type of multipolar ring machines with internal field-magnets, which originated with Messrs. Siemens

and Halske. The ring-winding is built up of separate copper conductors which are joined together in a simple continuous spiral. The outer portions of these conductors are made deep and broad, so as to serve as a commutator. The brushes trail on the outer surface of the ring; and it will be noted that there are as many sets of brushes as there are internal poles; the brushes are spaced out at equal angular distances;

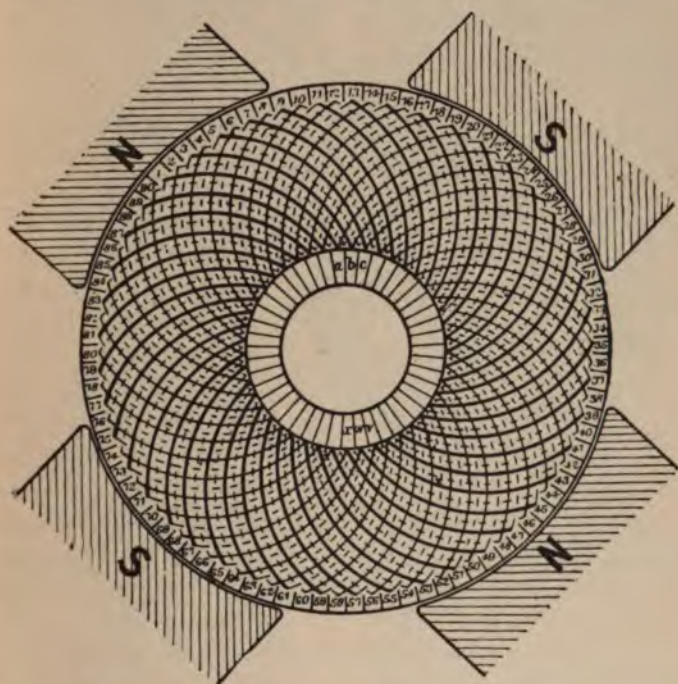


FIG. 192.—TRIPLE-WOUND 4-POLE DRUM ARMATURE.

there being 10 sets of them, alternately positive and negative. The 5 positive brushes are all connected together electrically; while the 5 negative brushes are also connected together. In this case there are 10 paths through the armature from the + to the - side of the circuit. It is, however, possible to reduce the number of brushes to two, by two independent methods, one of which connects the rows of sections in parallel with

multiple paths throughout the ring, the other puts them in series with but two paths through the ring.

In Fig 193 is represented a mode of reducing the number of brushes to two, by cross-connecting windings at opposite sides of the ring, a device due to Mr. Mordey. This may be looked upon as simply putting into parallel with one another each coil and the one that occupies the similar place opposite the corresponding pole. The arrangement looks unsymmetrical, but is not really so. For a 6-pole machine each coil would need to be connected with the two others at 120°

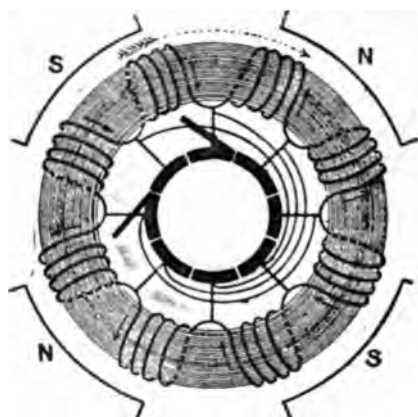


FIG. 193.—MORDEY'S METHOD OF
MULTIPOLAR CONNECTION OF RING
(PARALLEL CONNECTIONS.)

on either side of it. There are several actual ways of doing this. One is by means of spiral connectors; another is by connecting across the corresponding bars of the commutator. In the Victoria dynamos of the Brush Company (Fig. 283) the length of shaft between the ring and the commutator permits of double cross-connection, each junction of two adjacent sections being connected by a wire

down to the nearest bar of the commutator, and also connected round to that on the opposite side, as in Fig. 194. Such cross-connected machines really have four neutral points on the commutator, but the brushes collect the current from two only.

There are several methods of grouping the windings in series so as to gain a double electromotive-force. One of these modes, electrically symmetrical, is depicted in Fig. 195, wherein, while opposite coils are coupled in series, the commutator bars are cross-connected. This requires also but two brushes, at 90° apart. Two other modes of accomplishing the

same end are shown in the windings of Figs. 196 and 197. Here, however, the connections are not symmetrical, so that



FIG. 194.—CONNECTIONS OF VICTORIA (MORDEY) 4-POLE ARMATURE.



FIG. 195.—4-POLE RING, SERIES GROUPING (2 ROWS).

the resistances of the two paths (and therefore the respective currents) cannot be at all instants equal.



FIG. 196.—4-POLE RING, SERIES GROUPING (2 ROWS).



FIG. 197.—4-POLE RING, SERIES GROUPING (2 ROWS).

In yet another arrangement (Fig 198), each coil is connected down to p segments at intervals of $360^\circ \div p$ around

the ring and introduces an increased number of bars of the commutator.

Another winding, Fig. 122, devised by Professor Perry, brings down the connections from each section across a chord of the commutator. The one shown is that of a ring with

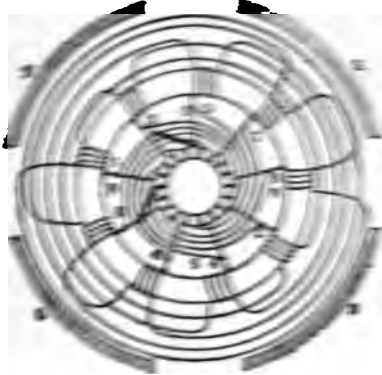


FIG. 122.—MULTIPOLAR RING.

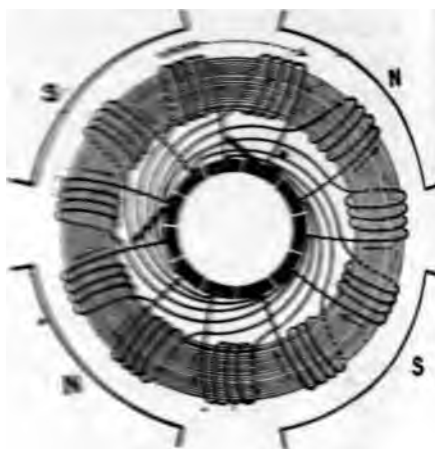


FIG. 123.—PERRY'S METHOD OF MULTIPOLAR SERIES-GROUPING.

eleven sections in a 4-pole field. The number of sections and of parts of the commutator must be odd if the number of pairs of poles is even. It may be either odd or even for 6-pole or 10-pole machines. Arnold points out that it is given by the formula:

$$Z = p y - 1.$$

Arnold¹ has described numerous other ring windings of complex kinds; and Parshall has given many examples.

DISK-WINDINGS.

These may in general be treated as drum windings extended radially, the outer periphery corresponding to the back end of the drum. The earliest such winding is that patented in 1875, by Pacinotti. This is a lap-winding

¹ *Op. citat.*

adapted for a 2-pole field, the N pole being behind the upper part, the S pole behind the lower part in the cut. It will be noted that the outer end of each radial conductor is carried round by a peripheral connecting piece to join the end of another radial conductor, which for a 2-pole machine would be the one lying next but one to that which is diametrically opposite. The schematic figure relates to a 10-part armature, made up of twenty radial conductors. They are numbered so that the order of connections may be traced. The diameter of commutation being d , the currents flow radially inwards in one half and radially outwards in the



FIG. 200.—PACINOTTI'S
DISK ARMATURE.

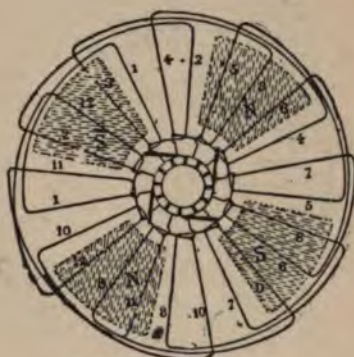


FIG. 201.—4-POLE DISK
LAP-WINDING.

other half of this disk. The construction of Pacinotti's experimental machines is described in his original paper.

Since then many suggestions have been made for windings of this description.

A lap-winding, identical with Pacinotti's, but adapted to a 4-pole field, is depicted in Fig. 201; it is known as the Edison "new disk" winding. The disk-armatures of Hookham's electricity meters are also lap-wound. Bollman and Müller have devised multipolar disks with wave-winding.

Fig. 202 shows the connections of a disk armature designed by Müller¹ for a 4-pole machine in which the conductors passing

¹ U. S. Patent, 331726 of 1885.

in front of the different pairs of poles are placed in series. The brushes in this case are placed at 90° to each other.

Disk-armatures have been revived by Desroziers and Fritsche. Desroziers employs for a 6-pole machine the elaborate wave-winding shown in Fig. 203. A special study of this class of winding has been made by Arnoux.¹ Fritsche

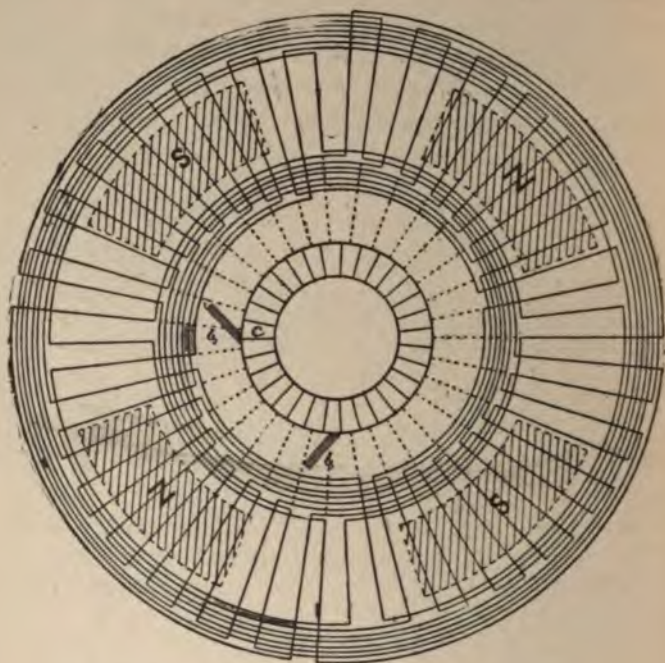


FIG. 202.—4-POLE WAVE-WINDING (MULLER).

employs polygonal poles, enabling him to use, as conductors, strips of metal built up in star-polygon fashion without any radial parts—a structural advantage. His disk, if developed out straight, would, for a 4-pole machine, be adequately represented by Fig. 189, p. 272. The two sets of conductors constitute two layers which are united at their outer ends to the bars of a commutator at the outer periphery.

¹ See reference, p. 244.

The main difficulty in the employment of disk-armatures has been in the construction of an armature of this sort which is mechanically strong and capable of resisting wear and tear. Desrozier has done much to overcome this difficulty, and has produced machines which are very widely used in France and her colonies. He discerned that a disk-armature can be separated into two parts ; that is to say, taking the alternate

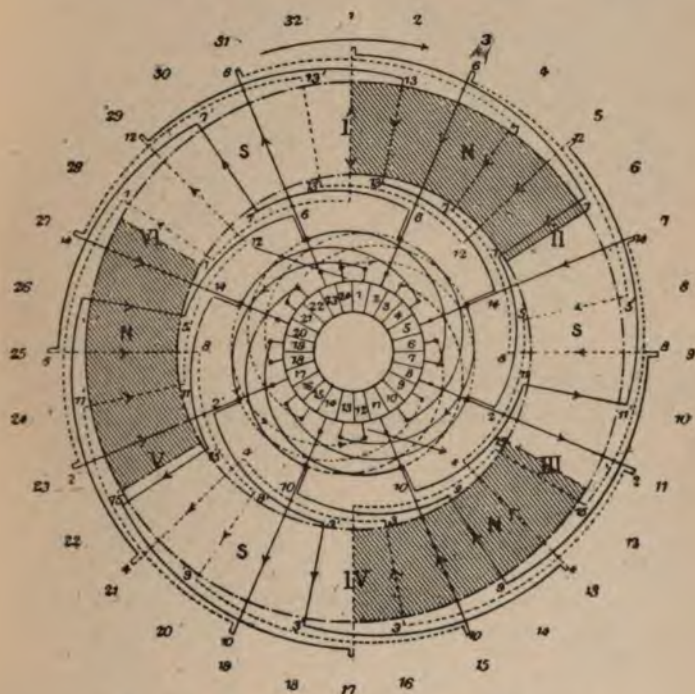


FIG. 203.—DESROZIER'S 6-POLE DISK-WINDING.

radiating conductors (the odd numbers for example), it is possible to build them and their connectors into a regular figure in one plane without troublesome over-crossings, and this plane of conductors can be superimposed upon a similar one built up of the other alternate conductors, so that the ends of the connectors coincide and only require to be soldered together to form a complete re-entrant winding.

This will be understood by reference to Figs. 204, 205 and 206. Fig. 204 shows six conductors joined in series forming part of a disk armature intended for a 6-pole field, the current

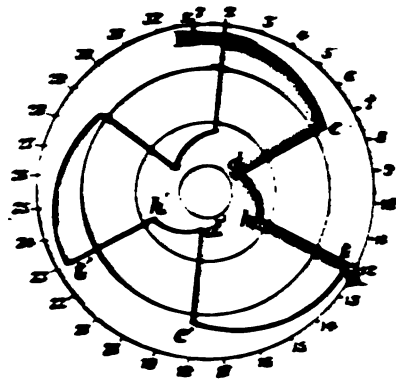
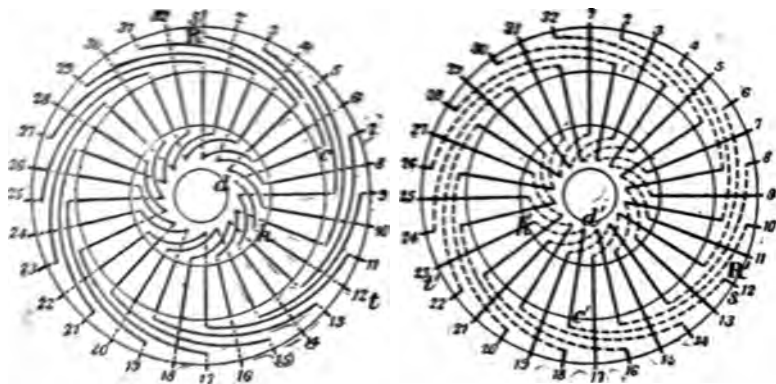


FIG. 204.—SKELETON DESROZIER'S WINDING.

flowing inwards when passing one pole and outwards when passing the next pole of opposite sign. In order to mount a number of these conductors in series, they and their connectors may be taken in pairs and half of them mounted in the manner shown in Fig. 205, in which the portion $R c d h t$ will be recognized from Fig. 204. The other half are mounted as in Fig. 206.

where the portion $R' c' d' h' t'$ is a continuation of the series in Fig. 204. In each of these planes of conductors the



FIGS. 205 and 206.—CONSTRUCTION OF DESROZIER'S DISK ARMATURE.

ds are brought out to the points, numbered 1, 2, 3, &c., to 32. By placing these two disks face to face, then

soldering up the coinciding ends and carrying those on the inside to the bars of a commutator we have a complete armature winding.

It is obvious that there are other ways of dividing up the series of conductors shown in Fig. 204 than the method adopted in Figs. 205 and 206. For instance, all parts similar to $R c d$, $R' c' d'$, &c., might be mounted to form one plane of conductors and the parts $d h t$, $d' h' t'$, &c., would then form the other plane. In high voltage machines where a number of turns per segment are required, this can be done in the manner shown in Fig. 207, where the same letters are used to denote corresponding parts.

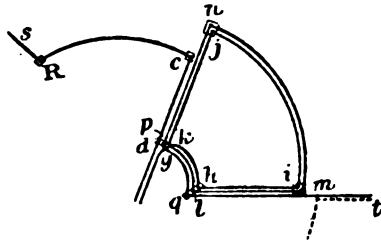


FIG. 207.

In practice there are two distinct methods of construction used: (1) wire-wound armatures; and (2) strip-built armatures. The wire in the former is threaded through holes in two concentric compressed cardboard rings that form the outer and inner supports for each plane of conductors. The two planes are then mounted face to face on a metal spider, the arms of which, radiating from the shaft, pass between the two layers of conductors.¹ Large machines of this type can be made which do not weigh more than 55 lbs. per horsepower. The efficiency is as high as that of good continuous-current machines of the ordinary type with cored armatures.

¹ For further particulars of these machines see *Electrical Engineer* (N.Y.), xvi. 259.

CHAPTER XIII.

PRACTICAL CONSTRUCTION OF ARMATURES.

LITTLE has yet been said about the proper modes of securing the armature-conductors, of insulating them, and of ventilating them. Most, though by no means the whole, of the present chapter, relates to continuous-current dynamos and motors; but much of it is equally applicable to alternators. Broadly, armatures having cores of iron may be grouped in two classes; those which have *surface windings* supported on smooth cores, and those which have *sunk windings* laid in slots or holes in the cores.

Armature Cores.—Cores are always laminated, being constructed either of (1) sheet-iron *disks*, (2) iron *ribbon*, or (3) iron *wire*. Ribbon is only used for discoidal armatures magnetized through the flanks. For drums and elongated rings disks stamped out from soft sheet iron, or from the best “mild steel,” are almost universal. The usual thickness is from 1 to 2 mm. (*i. e.* from 40 to 80 mils), but some makers go down to 14 mils. They should be of brands showing the least hysteresis. After being stamped out they should be annealed, and the burr at the edges removed. At this stage, if the cores are smooth (not toothed) it is usual to assemble them upon the shaft, turn them down truly in the lathe, then take them apart and remove the burr by grinding lightly on an emery wheel, then remount them. Before being finally mounted on the shaft they must be lightly insulated one from the other. For this purpose it is usual either to cover one face of each core-disk with varnished paper, or to enamel both faces of each core-disk. Mica insulation here would be too expensive, and it is not necessary. It is usual to make the end core-disks of stronger iron, sometimes as much as

12 mm. or $\frac{1}{2}$ -inch thick. For discoidal armatures the iron ribbon must be insulated with an interposed band of varnished paper. To stiffen a discoidal armature-core it is usual to build it upon a foundation ring of soft iron, and this in some cases is constructed with a projecting central iron web, on either side of which iron ribbon is coiled. An example is afforded by the core of the Victoria (Mordey) machine, Fig. 283, p. 418.



FIG. 208.—SEGMENTAL CORE-DISKS (KAPP).

For large machines the core-disks are built up in segmental portions to reduce cost. The cores are constructed, as shown in Fig. 208, of pieces which overlap in successive layers, each piece having eye-holes for bolts.

Wire cores were at one time largely in vogue, having been used by Gramme. The soft iron wire, varnished or slightly oxidized on its surface, was wound on a special former, then removed, taped externally, and wound with the copper wire conductors. Wire cores have three disadvantages: (i.) they are mechanically less satisfactory than disk cores; (ii) they fill a given core-space with an actually less nett cross-section of iron owing to the interstices between the separate wires, only about three-fourths of the total cross-section being occupied by iron; and (iii.) they present a discontinuity radially which offers an unnecessary reluctance in the path of the magnetic lines. The substitution of a square iron wire for a round one, is an improvement in all these respects.

Another mode of constructing wire cores was presented in the armature of the Bürgin machine, which originally consisted of several rings set side by side on one spindle, these rings being made of iron wire wound upon a square frame, and carrying each four coils. Mr. Crompton changed the square form to a hexagon having six coils upon it and increased the number of rings to ten. This form, however, proved to be in no way superior to an ordinary Gramme armature.

Toothed Cores.—Pacinotti's armature of 1864 (Fig. 211) was a toothed ring of solid iron supported on brass spokes and having boxwood distance-pieces fixed to the teeth to hold the windings apart. Armatures built up of toothed core-disks, consistently advocated by the author for the past twelve years, have been much used in recent time. They have four advantages over smooth armatures. (i.) The teeth present an excellent means of driving the copper conductors which lie between them; (ii.) the teeth may be brought very close to the polar surfaces of the field-magnet, with very narrow

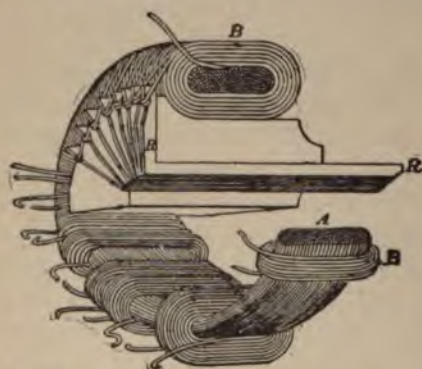


FIG. 209.—GRAMME RING WITH WIRE CORE.

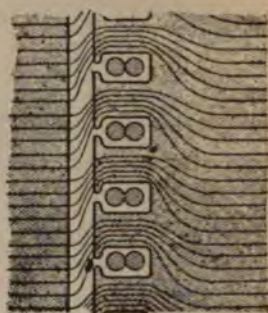


FIG. 210.—SUNK WINDING AND MAGNETIC DRAG ON TEETH.

clearance, thus bettering the magnetic circuit and therefore reducing the amount of copper required to excite the magnetic flux; (iii.) the drag comes almost entirely on the iron cores instead of on the copper conductors, as indicated in Fig. 210; (iv.) if the slots are deep the conductors are largely protected against eddy-currents. To set against these real advantages are the disadvantages of somewhat greater labor required in milling out the channels between the teeth of the assembled core; the extra difficulty of insulating the core from the conductors; and the liability of the teeth to set up eddy-currents (see p. 93) in the polar faces. The latter can be cured by making the teeth numerous and narrow, also by laminating the polar faces with grooves, and by enlarging the clearance.

Or by finally serving the entire armature outside the copper conductors with a layer of iron wire.

Toothed armatures were at one time much used by Messrs. Paterson and Cooper; but English makers generally have



FIG. 211. — PACINOTTI'S
TOOTHED RING ARMATURE (1864).



FIG. 212. — CORE OF ARMATURE
OF MOTOR (CROCKER-WHEELER.)

preferred smooth cores. In the United States, however, the smooth core is the exception and the toothed core the rule. Fig. 212 shows the form of armature core used in the small Crocker-Wheeler motor (Fig. 341). The core-disks are made, for convenience of winding, in two halves.



FIGS. 213, 214, 215. — TOOTHED AND SLOTTED CORE-PLATES.

Straight teeth (like Fig. 211) and triangular teeth (like Fig. 212) are, however, the exception. They are more usually T-shaped, and with rather deep slots between the teeth, as indicated in Fig. 213. Sometimes they are preferred in the

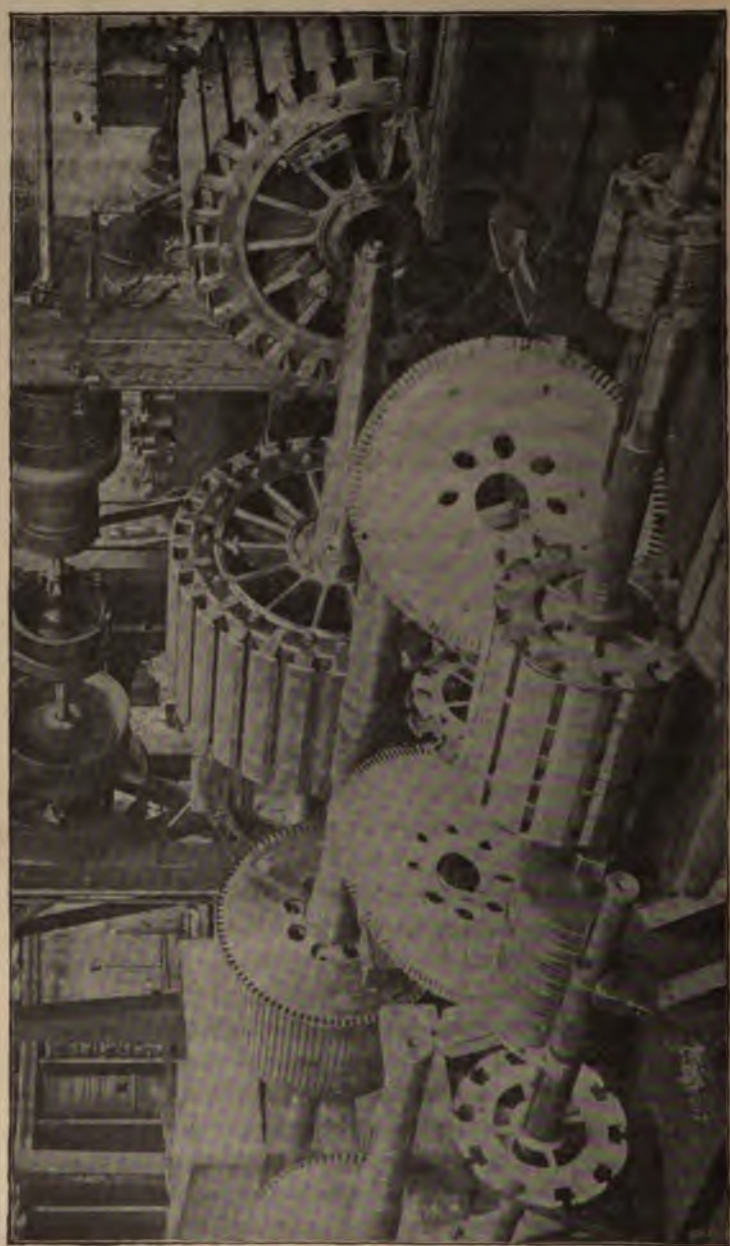


FIG. 216.—GROUP OF CORE DISKS (WESTINGHOUSE ELECTRIC CO.).

form of Fig. 214, which shows the slot as an oblong perforation with a narrow opening only at the periphery. Fig. 216 depicts a group of armature cores and disks in the shops of the



FIG. 217.—WIRING DRUM-ARMATURES (WESTINGHOUSE ELECTRIC CO.).

Westinghouse Company at Pittsburg. The cores with large T-shaped teeth are for alternators; whilst the cores with numerous narrow teeth are for continuous-current dynamos or motors. After the core-disks have been assembled on the shaft, the slots are very carefully filed out or reamed out, to avoid projecting edges that might cut the insulation. The mode of drawing in the insulated conductors of drum-armatures is shown in Fig. 217. In the armature which is being wired the slots are deep enough to admit of four conductors one above the other: this being intended for a high voltage winding. Compare also Fig. 347. With T-shaped teeth it is not necessary to apply binding-wires externally, the conductors being secured by driving a long wooden key into the slot after the wires have been inserted.

Pierced Core-disks.—The advantages offered by toothed core-disks are possessed to a still higher degree by core-disks



FIG. 218.
PIERCED CORE-DISK.

pierced with armatures just within the periphery. Such were independently suggested by Parsons, by Swinburne and by Brown. Wenström suggested slotted holes. In such armatures the conductors are carried in tubes of insulating material that pass through the perforations. This construction is eminently satisfactory from the mechanical and magnetic point of view. One peculiar and valuable property of the pierced core-disks

is, that they completely protect the embedded copper conductors, however massive, from parasitical eddy-currents which would otherwise be generated in them. The slots are often made oblong, as in Fig. 215, instead of circular. The standard style of hole used by Brown is about 50 millimetres long by 20 millimetres broad.

Driving-Spokes and Spiders.—Armature cores are usually built up upon an internal frame or skeleton pulley firmly keyed to the shaft. In small drum-armatures this internal

supporting frame may be omitted, the core-disks themselves being keyed directly on to the shaft. Some makers punch hexagonal holes in the core-disks and thread them on over a hexagonal shaft.

Frequently the core-disks are held together by insulated bolts passing through them, and driven by spiders keyed to the shaft, as in Fig 219. To this construction there is the objection that the bolt-holes reduce the effective cross-section of iron and strangle the magnetic flux. It is also needful that the bolts should be insulated from the arms of the spiders by ebonite washers and bushes, otherwise the framework will

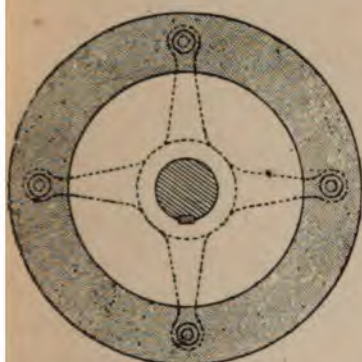


FIG. 219.—MODE OF DRIVING CORE-DISK.

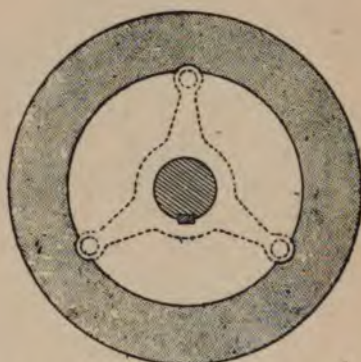


FIG. 220.—PATERSON AND COOPER'S MODE OF DRIVING CORE-DISKS.

constitute a closed circuit for eddy-currents which will heat it. A better mode is that used by Messrs. Paterson & Cooper, Fig. 220, in which the section of the iron is but slightly reduced and the bolts are entirely internal to the core.

Another mode is to provide the core-disks with dovetail notches into which pass long flanges from the shaft. Mr. Crompton, who introduced this construction in 1886, also used a method of connecting with the driving shaft by three grooves in the latter. In another form, a ribbed sleeve, which slips over the cylindrical shaft, is driven by a long feather. It is less costly and equally mechanical. Another form has the four projecting flanges in one solid structure.

Kapp's mode of driving the core-disks is shown in Fig 221, which should be compared with Plates I. and II. Over the shaft is slipped a long sleeve provided with three projecting flanges to support the core-disks. This sleeve, which is prevented from slipping by a long feather slightly sunk into a key-way, has the advantage of stiffening the shaft. In armatures for ring-winding, this internal structure is of gun-metal ; in those for drum-winding, of cast-iron. It is pushed up towards a face-plate which rests against a shoulder on the shaft, and the core-disks are tightened together between the

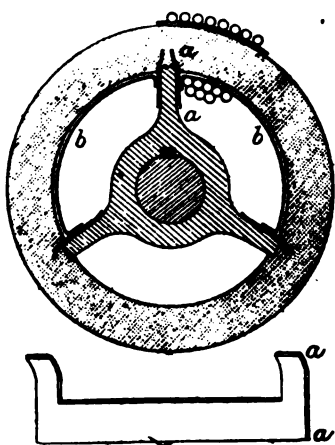


FIG. 221.—KAPP'S MODE OF DRIVING CORE-DISKS.

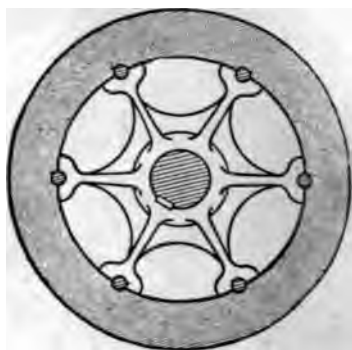


FIG. 222.—BROWN'S LATEST MODE OF DRIVING CORE-DISKS BY MEANS OF KEY-BOLTS.

two face-plates by a nut on the shaft. The lower figure shows the form of the strips of fibre used for insulating.

Figs. 222 and 223 show Brown's modes of supporting and driving core-disks. Fig. 223 corresponds with Plate VII.

In Fig 223, the spiders are two in number, each having four internal web-spokes and wide end-flanges. They fit over the shaft, with feathers to prevent turning. One of them is held up against a shoulder on the shaft, and after the core-disks have been assembled, the other one is pressed up by a large hexagonal nut. It will be noticed that two of the webs on each spider are ribbed ; the core-disks being stamped with

notches to prevent them turning. Of the four web-spokes two are long and two short, so that the core-disks may be compressed as the spiders are forced together. Many makers now use similar arrangements.

In Fig. 222, which is more recent, round steel keys are driven into grooves cut in the ends of the spider flanges, and in the core-rings.

The use of stout end-plates drawn together with screw

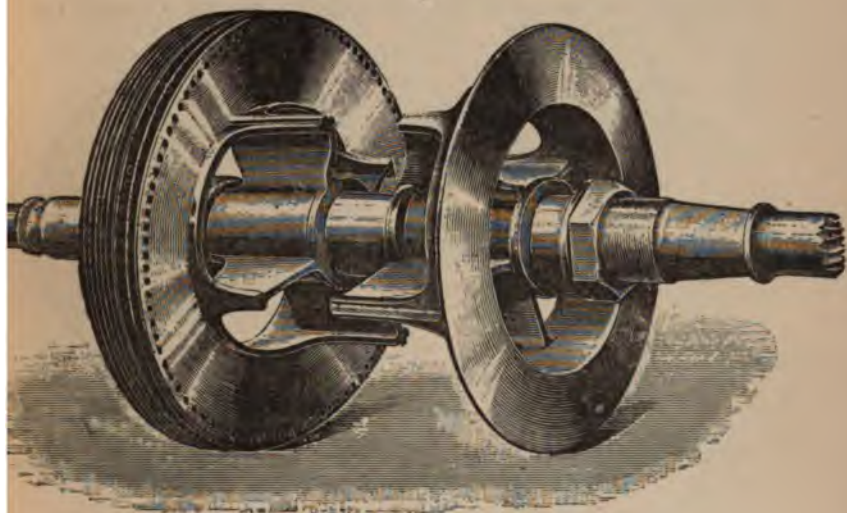


FIG. 223.—BROWN'S MODE OF DRIVING THE CORE-DISKS.

bolts to compress the core-disks is also illustrated in Brown's machine, built by the Oerlikon Co., Plate IV.

Another arrangement, admirable for its strength, is shown in Fig. 224. Upon the shaft are placed two gun-metal cones, with shallow feathers to prevent turning. In each cone are cut three slots at angles of 120° , the bottoms of the slots also sloping cone-wise. Into these slots fit three bridge-like gun-metal flanges, with projecting lugs at their ends, to hold up the core-disks. By screwing up a nut on the shaft the cones are pressed together, and thereby the three flange-spokes are

forced outwards and support the core-disks at three points of their internal periphery.

Another mode, shown in Plate X., is applicable to armatures of large diameter; the core-plates have internal notches to receive the ribs of the driving-centre.

It should not be forgotten that compressing stresses diminish the magnetic permeability of iron in the direction of the stress; and that tensile stresses increases the permeability.

Insulation of Iron Cores.—Mention has been made of the proper mode of insulating the core-disks internally from one

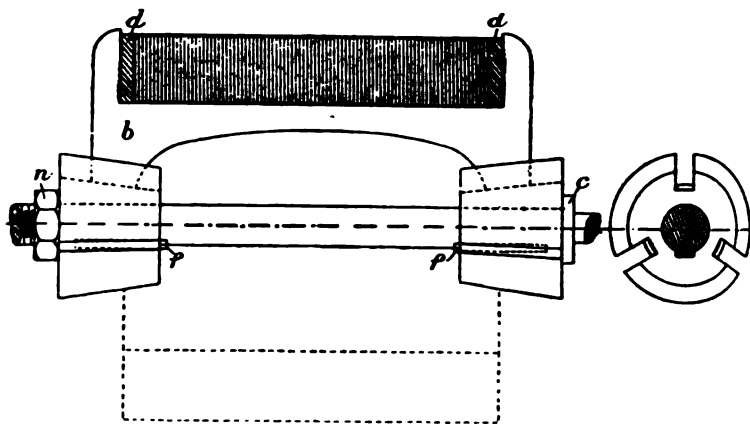


FIG. 224.—IMMISCH'S METHOD OF DRIVING BY TWO CONES.

another by interposing paper on enamel. At their peripheries they must be prevented from making metallic contacts with one another. But beside this internal insulation, they must be protected very carefully from *external* contact with the copper conductors. In the case of smooth cores it is usual to serve the completed core with one or two coats of enamel or japan, and then to cover it with a layer of some tough material such as canvas, manilla-paper, or Willesden-paper, well varnished with shellac varnish or with Scott's rubber varnish. Where tooth cores are used, channels of varnished paper, or of paper with mica strips laid between, are inserted veen the teeth. In the case of cores for ring-winding,

particular care must be taken to insulate the inner periphery and the driving spokes, where the internal windings lie near them.

Ventilation of Armatures.—Armature cores heat from three causes: hysteresis; eddy currents; and heat derived from the copper conductors. The careful lamination and insulation described above, are but means to prevent waste of power and to avoid risk of overheating. In the case of ring-wound machines there is usually an amount of surface exposed sufficient to get rid of the heat generated in the conductors without resorting to any special mode of ventilating. But in the case of large and solidly constructed drum-armatures, some mode of forcing the ventilation may be necessary. In drum armatures with the old-fashioned wire-windings overlapping the ends, adequate ventilation is impossible. As examples of ventilated cores the reader should see Kapp's drum-armature, Plate II., Fig. 1, and Brown's drum-armature, Plate VII. There are special ventilating ducts in the armature of the large street-tramway generator, Plate X.

In the case of drum-windings having end-connections built up, the arrangements with one set of evolute spirals and one set of straight radial pieces (as in Fig. 177, p. 263) are sometimes preferred to those with two sets of spirals as in Fig. 179, p. 264, as having a better fan action. Some makers use spiders with arms sloped like the sails of a windmill, so as to propel air through the interior of the armature.

Balancing of Armatures.—It is very needful that armatures should be properly balanced, otherwise they will set up injurious vibrations in running. Most makers test their armatures for balance by laying the journals on two parallel metal rails (or "knife-edges") and noting whether the armature will remain in any position without tending to roll. It is well indeed to balance them thus on completing the core ready for winding, and again after winding. If the end core-disks have been made of thick iron, holes can be drilled in these to restore perfect balance; or leaden plugs can be inserted.

It may be remarked that this mode of observing the statical balance is not perfect; for if the masses that balance

around the axis are distributed unsymmetrically along the axis, there will be, when running, a tendency to vibration.

Driving-Horns.—It is of primary importance that the armature conductors should be properly driven, otherwise they may be raked out of place by the tangential drag in the magnetic field (p. 99). In the case of ring-windings, such injurious action is less likely to occur than with drum-windings, as the convolutions which thread through the interior of the core tend to bind, and press against the driving-spokes. But even here, it is found needful to provide positive driving at a number of points around the periphery. Crompton found it needful to drive boxwood wedges in between the core-disks. He then adopted a construction in which pieces of fibre are inserted at intervals for ventilation between the core-disks; the gaps so left being convenient for the insertion of driving-horns between the wires. Kapp used projecting narrow steel horns protected by pieces of hard fibre. Goolden used strips of hard white fibre inserted into shallow keyways milled out of the surface of the core and held in by external binding-wires. For discoidal armatures the driving-horns must project at the flanks, being inserted between the core-ribbons.

Binding-Wires.—In the case of smooth cores the conductors must be secured in their places by a number of external bands, known as *binding-wires*. These must be very strong, to resist centrifugal force and to hold the conductors from being dragged aside; and yet at the same time must occupy very little radial depth, that the clearance between conductors and pole-face may be as narrow as possible. The almost invariable practice is to employ a tinned wire, of hard-drawn brass or steel, which, after winding, can be sweated together with solder into a continuous band. It is impossible to give rules for the sizes of binding-wires. A frequent size for steel wire is 40 mils, or a little under 1 mm. diameter. The wire is wound on in bands of from 10 to 30 turns each, the separate bands being spaced out at distances of from 1 to 2 inches apart. Under each belt of binding-wires a band of insulation must be laid. This usually consists of two layers; first a strip of thin vulcanized fibre slightly wider than the

band of wires, and then a strip of mica (in short pieces) of about equal width. Some makers lay a small strap of thin brass under each band of binding-wires, having ends which can be turned over and soldered down to secure the two ends of the wire from flying out. The armature depicted in Fig. 225 is a drum-armature, having six sets of binding-wires. As an example it may be stated that Mr. Esson recommends for a smooth drum-armature 10 inches in diameter and 12 inches in length, six bands of 18-mil (*i. e.* No. 26 B. W. G.) wire, each band being about $\frac{5}{8}$ inch wide, and containing about 33 turns; the bands being, therefore, rather less than $1\frac{1}{2}$ inches apart. On a drum or ring 20 inches in diameter he would use 35-mil wire, in bands $\frac{1}{2}$ inch wide, about 2 inches apart.

In the standard multipolar dynamos of the General Electric Co. (see Fig. 292), phosphor-bronze bands are now used instead of binding-wires.

In the following table are given the particulars of the bindings adopted in some of the smooth-core drum-armatures of the Edison standard bipolar dynamos.

Output of dynamo in kilowatts	1	10	30	50	150
Revolutions per minute	2100	1600	1200	700	450
Length of armature body (inches)	6 $\frac{1}{2}$	12	18	24 $\frac{1}{2}$	26 $\frac{1}{2}$
Diameter of armature body	3 $\frac{1}{2}$	6 $\frac{1}{4}$	9 $\frac{3}{16}$	12 $\frac{1}{8}$	23 $\frac{1}{4}$
No. of binding bands on body	6	7	9	13	7
No. of strands in each band	22	19	21	18	24
Gauge of brass binding-wire (B.W.G.) . .	25	23	21	19	19
Width of mica underlay 0.01 inch thick	$\frac{5}{8}$	1	1	1 $\frac{1}{2}$	1 $\frac{1}{2}$
Number of clamps (of copper sheet, 14 mils thick and $\frac{1}{8}$ to $\frac{1}{4}$ -inch wide) on each band	2	3	4	4	6

Winding Armatures.—Given a scheme of winding according to any of the modes discussed in Chapter XII., the problem remains how to carry it out in the factory. Ring-windings may be considered first, then drum-windings. A broad distinction may be set up between wire-wound armatures and those with built-up windings consisting of bars and

connectors, or of specially constructed portions that are put together instead of being wound on. Wire-wound armatures are usual for outputs below 100 amperes, including all arc-lighting machines. Single round wire, insulated with double cotton covering soaked afterwards with shellac varnish, is usually adopted for small machines and arc-lighting dynamos. Silk-covered wire is rarely used. For small electroplating dynamos it is frequent to use several round wires in parallel, even to as many as twenty or thirty separate wires side by side. Wire-drawers will furnish rectangular wire of any desired

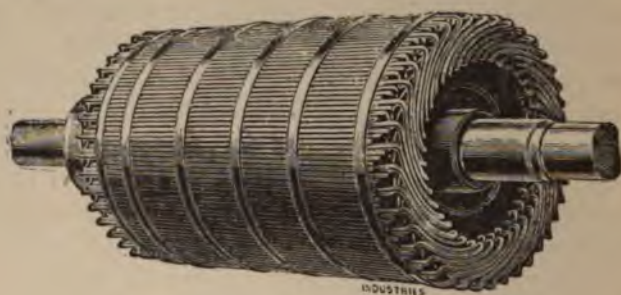


FIG. 225.—ALIOOTH'S DRUM-ARMATURE.

section ; but for greater flexibility in winding, a rectangular conductor made of three or four separate strips laid side by side and then served with a coating of tape to hold them together, is preferable. It has the advantage of partially eliminating eddy-currents in the conductors themselves.

For armatures having outputs exceeding 200 amperes bar-armatures are preferred, owing to the inflexible nature of wires that are thick enough to carry these currents. The two classes comprise several varieties as under :—

WIRE-WOUND ARMATURES.

Single round wire.
Two or more round wires in parallel.
Stranded wire.
Single square wire.
Single rectangular wire.
Laminated strip conductor.

BAR-ARMATURES.

Round bars.
Rectangular bars.
Imbricated rectangular strips.
Rectangular bars of compressed stranded wire.
Special forgings.

For bar-armatures, rectangular bars set edgewise to the core are more frequent than round bars; but armatures in which solid bars are set on the outside of a smooth core are liable to a serious waste of work that does not occur with wire-wound armatures. When the conductors present a considerable breadth, eddy-currents are set up in them as they enter or leave the magnetic field, owing to the fact that one edge of the bar may be passing through a field the density of which is very different from that of the field through which the other edge of the same bar is passing. Assuming a peripheral speed of 1700 to 1800 feet per second, it is found in practice impossible by any shaping of the pole corners to avoid excessive heating of solid copper bars on the armature if their breadth exceeds 5 mm. The work wasted in producing these eddy-currents may even reduce the efficiency of the dynamo by more than 5 per cent. This does not, however, occur in those armatures in which the bars are sunk deeply between teeth, or pass through holes in the core-disks. To reduce such losses, bars are made of several strips oxidized on the surface, or lightly insulated by oiling or enamelling, and uniting only at their ends, have been used. Crompton¹ has proposed several modes of twisting or imbricating around one another two or more strips, so as more effectually to neutralize the eddy-currents. More recently he and other makers have used bars made of stranded copper wire compressed into a rectangular form, each wire being oxidized or slightly insulated.

Yet another mode of armature construction, described later, consists in winding the insulated wires or strips upon special formers or moulds, in groups which are afterwards laid on or around the armature core. One advantage in such methods is the greater ease of securing perfect insulation between those parts of the windings which differ greatly from one another in potential. In drum-windings, if the conductors lie in one layer, there is an extreme difference of potential between each conductor and its next neighbor

¹ See *Journal Institution Electrical Engineers*, xix. 240, 1890.

Whereas if they lie in two layers, an intermediate sheet of insulating material can be laid between. A two-layer winding is extremely convenient in drum-armatures, as it facilitates connections.

Wire-wound armatures are usually well served with shellac varnish or india-rubber solution after the winding is completed. They should be well dried in a stove at steam-heat after varnishing.

Modes of Winding Ring-Cores.—When a smooth ring-core is to be wound it is frequent to stencil upon the end faces a number of radial lines corresponding in breadth to the

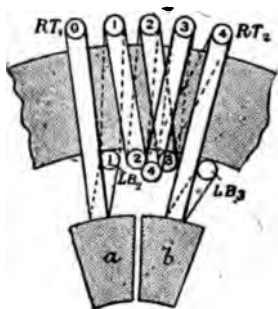


FIG. 226.—WINDING DIAGRAM.
RING-ARMATURE.

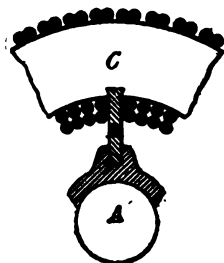


FIG. 227.—CROMPTON'S
WIRE-WOUND ARMATURE.

separate sections, so as to guide the winder in his work. With toothed cores no such plan is needed.

Ring-winding is, in general, easy; nevertheless care must be exercised. The separate "sections" of the coil are almost invariably wound on the cores separately, leaving the ends projecting, secured temporarily with string, and these ends are subsequently connected together and to the commutator. An inexperienced workman may easily connect up wrongly; making a left-handed winding instead of a right-handed one or *vice versa*. Hence it is well to provide him with some such working drawing as Fig. 226, which relates to a right-handed winding having four turns in each section. The wire marked "o" is the last or outer end of the section previous to that considered. This end will eventually be brought down to a

bar *a* of the commutator, and from this bar will go out the beginning or left-bottom end, marked L B, of the section in question. Looking at this diagram the winder will see that the wire L B must pass under the core to the far end and then return over the top, thus making turn No. 1. It will then bend down to the right, be threaded through again, and make turn No. 2; again, and make turn No. 3; but as the inner space is narrower than the outer space, turn No. 4 will probably have to ride on, or partly bed between, the turns already wound. The right-top end, marked R T, will eventually be joined to bar *b* of the commutator. If the winder is shown that the right-top wire of one section joins the left-bottom turn of the next section at the commutator, he will have no excuse for mistakes. One way of arranging the windings on a ring, with two layers internally and one externally, is shown in Fig. 227. The winding of multipolar rings is sufficiently considered in the previous chapter.

For arc-lighting armatures, and in general those which have numerous convolutions of wire to each section, it is convenient to prepare the wire in separate lengths sufficient for each section, and to coil each length on small shuttles, each length being wound upon *two* shuttles which are alternately used for successive layers. By this device both ends of the wire that constitutes a section are brought to the outside instead of one of them leading directly down to the bottom layer, as in ordinary bobbin winding.

For those machines that only require one, or two, complete turns to each section, it is common to have the copper conductors prepared beforehand upon separate formers, and ready taped to be slipped on over the cores. Crompton introduced the forms illustrated in Fig. 228, consisting of drawn copper of nearly rectangular section twisted at the ends so as to pack closely in the interior of the ring. These conductors are sprung on over the ring-core, and afterwards are coupled up so as to make a continuous winding.

In the large multipolar ring dynamos with internal field-magnet and external commutator, now so much used for central stations in Germany, the windings are so constructed that

their outer part serves also as commutator, as in Plate VIII. The armature consists of core-rings built up of segmental plates shown in section at *b*, Fig. 229, supported by driving-rods *a* which pass through them. After being covered with suitable insulation, the copper conductors *c d* are slipped on over them and coupled up to make a continuous spiral winding. The insulation between is usually a preparation of paper. The

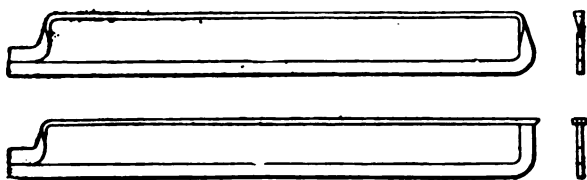


FIG. 228.—WINDINGS OF CROMPTON'S ARMATURES (1886)

outer part *d* of the copper conductor is made both deep and broad, and serves as a commutator bar. The brushes (not shown) are fixed upon the projecting bar *e*, and trail on the outer periphery of the copper windings of the ring. At *f* is a lever for raising the brushes out of contact.

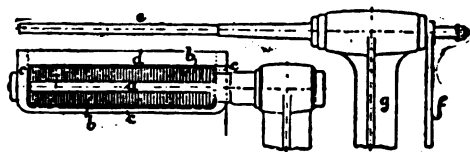


FIG. 229.—CONSTRUCTION OF GERMAN MULTIPOLAR RING-ARMATURE.

Drum-Winding.—Drum-armatures of all types may all be regarded as modifications of Siemens' well-known longitudinal shuttle-form armature of 1856, a multiplicity of sections of the coils being employed to afford continuity of the currents. The drum pattern was invented in 1872 by von Hefner Alteneck, of the firm of Siemens and Halske, of Berlin. In this system, as in the Gramme ring, the successive "sections" or groups of coils that are wound on the core, are connected together continuously, the end of one section and the

beginning of the next being both united to one segment of the commutator. It is important to note a difference between drum and ring-winding. In a ring-winding the volts induced in any one section (at a given speed) depend only on the magnetic field at one side of the armature; but in a drum-winding the volts induced in any one section depend on the two magnetic fields at the two sides, since each winding wraps over the drum nearly diametrically. As a result, drum-wound armatures are less liable to spark, and they suffer less than ring-wound armatures from inductive reactions.

The advantages of the drum form of armature appear to be (1) that they require less wire than the ring-armature of equal size; (2) are free from liability to false inductions (p. 68), and therefore more independent of the form of the pole-pieces; (3) have smaller cross-magnetizing tendency than ring-armatures. Their disadvantages hitherto have been: (1) greater difficulty of construction; (2) greater difficulty of securing proper insulation on account of over wrapping of end conductors; (3) greater difficulty of ventilation; (4) greater difficulty of executing repairs.

Siemens' Winding.—In some of the earlier patterns of Siemens' machines the cores of the drum were of wood, over-spun with iron wire circumferentially before receiving the longitudinal winding. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. The process of constructing the armature employed down to the year 1885 is illustrated in Fig. 230; there being two layers of coils all over the drum. Although, for the sake of rendering the connections more intelligible, the commutator is shown in Fig. 230 in its place on the axle, it is not, as a matter of fact, put into its place until after all the sections have been wound, the end of the wires being temporarily twisted together until all can be soldered to the connecting strips of copper.

So far all is simple, but when we pass on to the construction of bar-armatures, new complications arise.

To connect the conductors of a bar-armature across the

ends of a drum is not so simple a matter as might at first appear. Suppose that a scheme of connections has all been worked out beforehand and that a winding-table has been

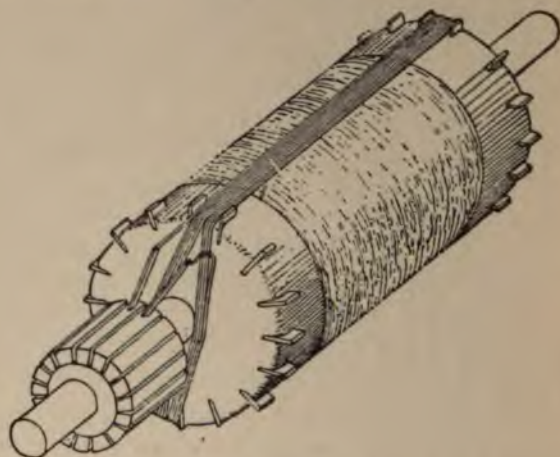


FIG. 230.—METHOD OF WINDING SIEMENS' ARMATURE.

prepared in which the order of the end-connections is set down. It yet remains to determine the mechanical devices for the end-connectors which shall be compatible with

working conditions. The end-connectors must be good conductors, sufficiently well insulated from one another, allowing of repairs and ventilation, and mechanically sound. Wire-wound drums often present an ugly overwrapping at the ends, which stops ventilation and hinders repairs. Quite early, Messrs. Siemens devised, for their electroplating machines, a system of uniting by spiral connectors (Fig. 231) the



FIG. 231.—SIEMENS' BAR-ARMATURE.

ends of the copper bars. To connect any bar with that lying next to the one diametrically opposite, two evolute

spiral strips of copper were applied, one bending inwardly, the other outwardly, their junction being mechanically secured to a block of wood on the shaft. Their outer ends were attached to the bars by silver solder. At each end of the drum these spiral connectors constituted two separate layers. These systems of evolute spirals, with more or less modification, are to be found in the majority of recent drum-armatures. A common form of conductor cut from sheet copper is illustrated in Fig. 232; a second form is made of strip folded.

Edison's modification of the drum-armature was alluded to on p. 260. It was manufactured under a royalty from the

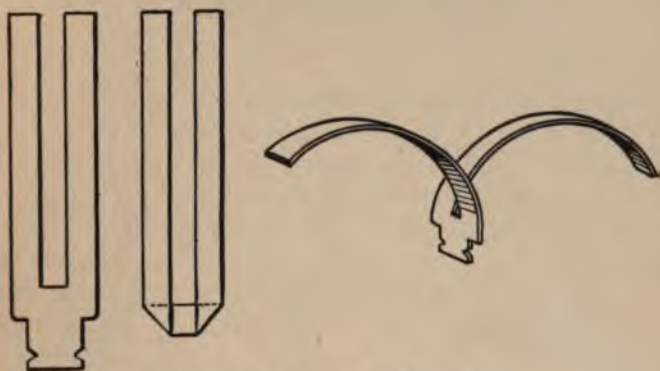


FIG. 232.—EVOLUTE CONNECTORS.

Siemens patents until the expiry of the latter. In Edison's larger dynamos of the years 1883 to 1885, the armature was constructed of solid bars of copper, arranged around the periphery of a core consisting of thin iron disks separated by mica or paper. Fig. 233 shows the armature removed from the machine. The ends of the bars are connected across by washers or disks of copper, insulated from each other, and having projecting lugs, to which the copper bars are attached. The construction was mechanically excellent, but it did not admit of ventilation; and the stray field at the ends of the armature set up eddy-currents in the substance of the copper disks. It was abandoned in favor of better methods.

In the Hopkinson armatures built by Mather and Platt, a return was made to the system of evolute conductors. The construction, as carried out for a machine in which there is one convolution in each section of the winding is indicated in Fig. 234.



FIG. 233.—ARMATURE OF EDISON DYNAMO.

The core, which is built against a shoulder on the shaft, consists of numerous disks of thin iron, but with a few thicker core-disks *d, d*, interposed at the ends and at intervals between. These are clamped up by nuts at the end near the commutator *C*. The conductors of copper are provided with driving lugs

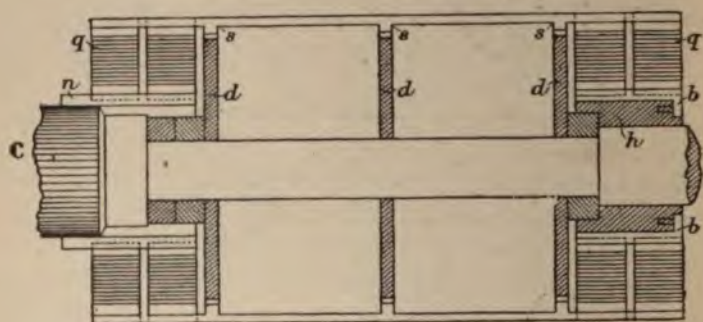


FIG. 234.—SECTION OF HOPKINSON'S DRUM-ARMATURE.

s, s, which, properly insulated, project into notches cut in the thick core disk. The systems of spiral connectors are shown in section at *q q*. At the commutator end they join the conductors down to a set of copper pieces *n*, which run to the corresponding bars of the commutator. At the other end

the spirals are inserted into a set of copper pieces *b* assembled around a wooden hub *h* by which they are driven, being screwed in through end lugs. For armatures in which each section consists of two convolutions, it is necessary to provide four layers of spiral connectors at each end.

Many successive modes of drum connection have been tried by Mr. Crompton. In conjunction with Mr. Swinburne he devised a method of connecting the conductors of a drum-armature which enables the core to be ventilated. The fundamental point in this construction was illustrated in the former edition of this work, and consisted in the use of cranked ends to the bars, together with spiral evolute connectors to join across diameters at the ends. The same method of connecting was applied to Swinburne's plan of chord winding (p. 246).

The difficulty of getting at the inner spirals when they are disposed in two layers led to another suggestion by Crompton and Kyle, namely, turn the spiral connectors outward instead of inward, at the ends of the drum, which thus becomes enlarged in diameter.

The recent modes used by Crompton for drum-armatures are sketched in Figs. 235 and 236.

In the first of these, which is for a 2-pole dynamo, the spiral connectors, stamped out of sheet copper, are driven by mechanical attachment to a clamping sleeve keyed to the shaft. In the second, which is for a 4-pole machine, the spiral connectors, being shorter, do not require to be similarly tongued. The conductors or armature bars are made of stranded wire compressed to rectangular section.

A recent armature built by the Oerlikon Company is shown in Fig. 237. It belongs to the 60-kilowatt machine described on p. 415, and is a good example of a 4-pole drum with evolute connectors. The core-disks have straight teeth between which the conductors lie in pairs side by side.

A method based on that of Paris and Scott is used by Kapp both for bipolar and multipolar drums. The connectors are stamped out from thin sheet copper in the form of semi-circular or quadrantal arcs, provided with lugs (as shown on

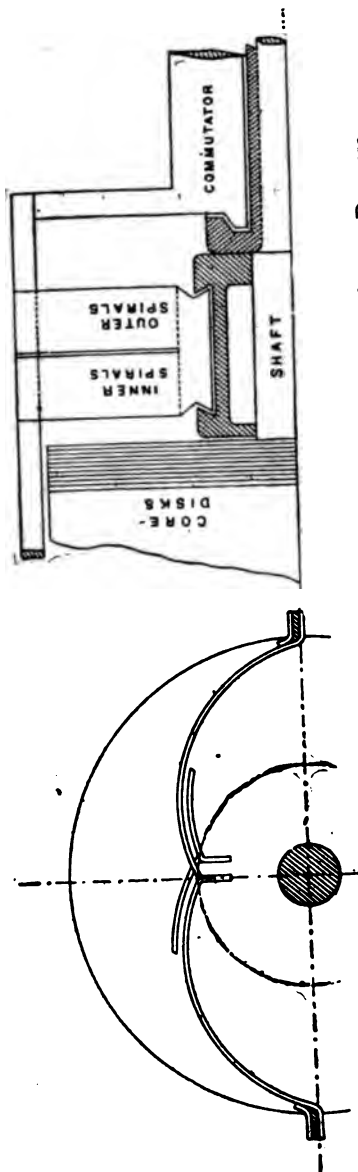


FIG. 235.—CROMPTON DRUM-WINDING FOR CENTRAL STATION MACHINE, 2-POLE DYNAMO.

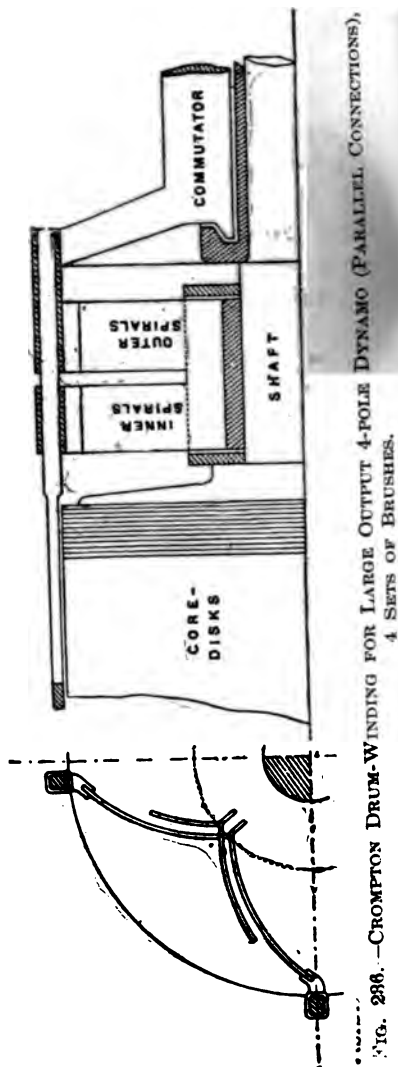


FIG. 236.—CROMPTON DRUM-WINDING FOR LARGE OUTPUT 4-POLE DYNAMO (PARALLEL CONNECTIONS),
4 SETS OF BRUSHES.

Plate II. Fig. 2) which can be bent, one forward, one backward, thus enabling connections to be made by a whole series of such connectors arranged skew-wise, with suitable insulation

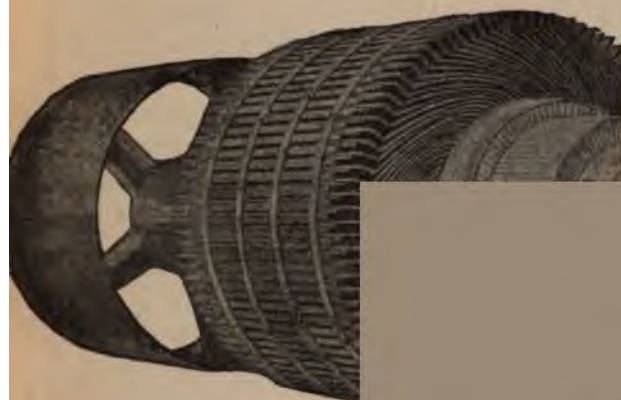


FIG. 237.—4-POLE DRUM-ARMATURE OF OERLIKON CO.

between, in a carriage or bobbin mounted on the shaft. The connectors are assembled together to the proper number, and held in with binding wires in the channel of this carriage,



FIG. 238.—SEPARATE SECTION OF EICKEMEYER'S ARMATURE.

which is then put in place, and the lugs are soldered into grooves cut in the ends of the armature conductors, which for this purpose are made alternately long and short at their ends. The best way to understand this method is to make a few

model connectors in paper or cardboard, and lay them over one another.

Eickemeyer's methods of construction, which have been largely used in the States, and also in England by Mr. Parker, are distinctive in that the individual "sections" of the winding, whether consisting of one single turn, or of a large number of turns of small wire, is first shaped upon a separate former, and each such section is separately insulated. Afterwards the sections are assembled in their places upon the core of the drum. Fig. 238 shows one of the forms given to the sections. The lower part will form part of an inner layer, and the upper part, which is longer, will form part of an outer layer in the



FIG. 239.—EICKEMEYER'S ARMATURE, COMPLETE.

assembled windings. The completed armature, with its binding wires, is shown in Fig. 239.

The cylindrical pattern of drum-armature adopted by Brown is shown in Fig. 240, and in detail in Plate VII.

The conductors (in holes through the core disks) lie in two layers, and the end-connections are made without evolutes or any other parts that would cover up the end-faces of the drum. The conductors being extended and bent, the outer layer to left, the inner to right, thus continue the cylindrical surface, which projects at both ends beyond the core. It has the advantage of a good ventilation and accessibility. In Plate VII. it will be seen that these projecting cylindrical ends are supported by an internal flange attached to the stout end core-plates. This mode of connection has been used by Brown since the beginning of 1892 for drums, and is also adopted for tank windings in alternate-current generators and in the

rotating parts of all alternate-current motors, both single and polyphase, that have windings upon them. It has since been adopted by both the Westinghouse Co. and by the General Electric Co. The Allgemeine Co., of Berlin, uses a somewhat



FIG. 240—CYLINDRICAL WOUND DRUM-ARMATURE (4-POLE) (BROWN).

similar plan of end-connections, but the sunk conductors lie in one layer only. A very similar mode of winding was patented by Hon. C. A. Parsons. But the arrangement with one layer is less convenient as it requires that alternate conductors should bend under the others, since there must be two layers of connecting-pieces sloping in opposite ways.

CHAPTER XIV.

COMMUTATORS, BRUSHES AND BRUSH-HOLDERS.

DYNAMOS for furnishing continuous currents require a *commutator* (sometimes called a *collector*) and *brushes* to collect the current. The essential action of these organs has been already described (see pp. 78 and 80) ; and the causes that give rise to sparks are discussed in Chapter IV., p. 81, and in Chapter XVI. We have now to consider the design and construction of these organs.

We may distinguish three types of apparatus for collecting the currents from dynamo machines.

I. Continuous-current dynamos with closed coil armatures as used for incandescent lighting and other work requiring a constant or nearly constant potential, are furnished with a commutator of the Pacinotti type, that is to say, consisting of a considerable number of parallel bars secured around an insulating hub, and presenting a cylindrical surface, against which press a pair (or in some cases more than one pair) of brushes or sets of brushes.

II. Continuous-current dynamos of the open coil type, as used for arc lighting, and giving a constant or nearly constant current, are provided with a commutator consisting of a comparatively small number of segments, each covering a considerable angle, and separated by air-gaps from one another. These are described in Chapter XVIII.

III. Alternators with revolving armatures need a pair of collecting rings of metal, each provided with one or more brushes, or some analogous device to form a sliding connection with the circuit. Alternators with revolving field-magnets of which the winding also revolves, need a similar device to connect the exciting current to the moving coils. These devices are

considered at the end of the present chapter, which is in the main devoted to apparatus of the first of the three classes enumerated.

Commutator Bars.—The number of bars of the commutator depends on the scheme of winding and on the number of sections in which the armature winding is grouped. Increasing the number of bars diminishes the tendency to spark (p. 83); and lessens the fluctuations of the current (p. 178). An even number of bars is preferable to an odd number; and for ring-wound armatures the cores of which are usually carried on three-armed spiders, it is preferable that the number of bars should be a multiple of three. There are, however, two practical reasons against making the number of bars very great. Increasing the number increases the cost. Again, in large machines having but one turn of the armature winding from each bar of the armature to the next, the number cannot be greatly increased without exceeding the voltage desired. For example, in a bipolar Edison-Hopkinson machine for an output of 1100 amperes at 105 volts, only 43 convolutions are required. On the other hand, it is found for small dynamos, that if the number of bars is increased, each bar becomes so thin that a brush of the proper thickness to collect the current would bridge more than two commutator bars at once. Again the bars should be of a length proportioned to the number of amperes that is to be taken off at them. Modern practice varies somewhat, but it may be fairly represented by some such figure as 1.2 inches for every 100 amperes. The mode of attachment of the bars should be such as to make the greatest amount of length available. They should also be of considerable radial depth, to allow for wear, as the commutator needs to be turned down from time to time to preserve cylindricity. As for the material, most makers use hard-drawn copper, made in long lengths of the proper section, and cut off to the length required. Some American makers use drop-forgings of copper, stamped to shape with projections for clamping and connecting to the windings. Commutators to be used with carbon brushes need to be made from $1\frac{1}{2}$ to 2 times as large as they need be

if copper brushes are used, for the carbon brushes require to touch over a larger amount of surface (for the same current), but ought not, except in the special cases of duplex and triplex armatures (p. 272), to touch more than two commutator segments at one time.

Insulation.—It is needful to have a good insulation between each bar and its neighbours, and a specially good insulation between the bars and the sleeve or hub around which they are mounted, and also between the bars and the clamping devices that hold them; for the difference of

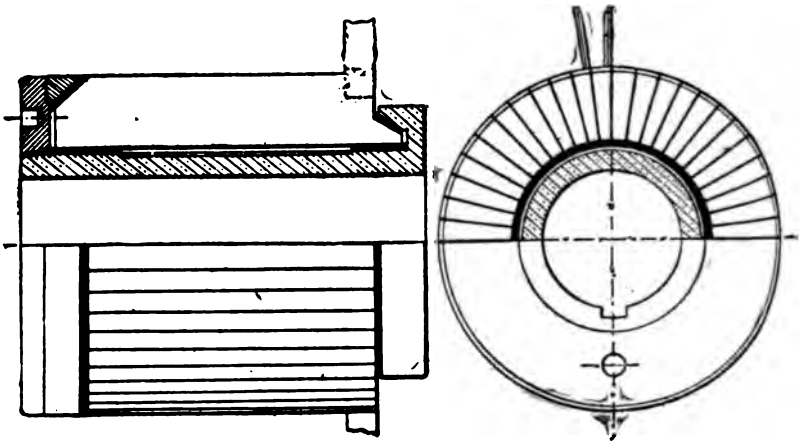


FIG. 241.—SECTION OF COMMUTATOR (PATERSON AND COOPER).

potential is small between neighboring bars, and much larger between the bars and other metal-work. The insulating material must not absorb oil or moisture: hence asbestos and plaster are inadmissible. Vulcanized fibre and Willesden paper are not by themselves adequate, though mechanically strong, as they are both liable to absorb moisture. Mica is the one satisfactory material used by English and American makers; but in Germany a preparation of paper is frequently substituted. Washers of conical form are sometimes built up of thin pieces of mica held together by shellac and consolidated while hot under great pressure. Between

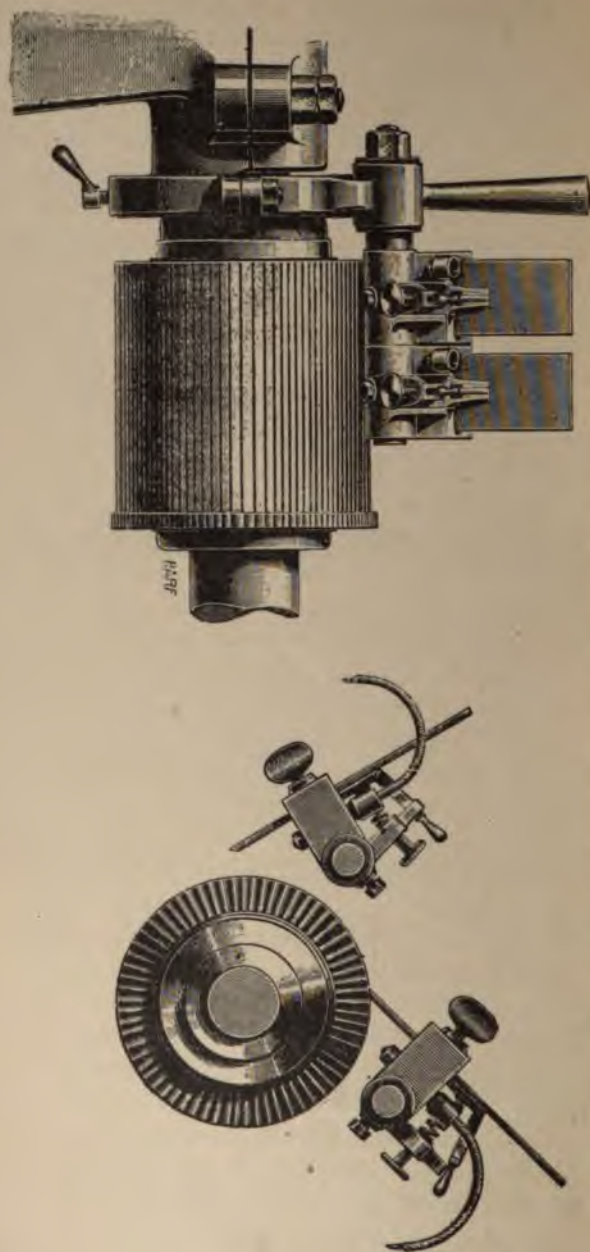
the bars mica may be used very thin with advantage. Commutators with air-gaps between the bars have been used. But with air-insulation there is some trouble in keeping the gaps from being filled by metallic dust from the wearing of the brushes.

Construction of Commutators.—In the construction shown in Fig. 241, the bars are clamped in place by fitting at one end into a groove in a gun-metal sleeve, and at the other by an external clamping ring which is forced over their bevelled ends by a large screw-washer. The insulation is carried out by thin slips of mica between the bars, and layers of mica and vulcanized fibre around the sleeve and clamping surfaces. The clamping ring in this case reduces the available surface for the brushes.

In the Gülcher Co.'s machines a construction is adopted which is illustrated by Figs. 242 and 243, and of which a section is given in Fig. 244. The drawings relate to a four-pole machine with only two sets of collecting brushes. Here, also the bars of the commutator are assembled around a sleeve fixed on the shaft, but are so arranged that their whole length is available for contact with the brushes; being held in position at their ends, with insulation between the V-shaped nicks in the bars and the clamping pieces which enter them.

A very similar arrangement obtains in Kapp's dynamo (Fig. 1, Plate II.), in which the clamping nicks in the ends of the bars are made deep; the end insulation being effected by three rings of vulcanized fibre, one flat, the other two conical, which fit into the ends of the assembled bars. It is good that a sufficient length of insulating surface should exist between the bars and the metal mountings, for there is less likelihood of a fault occurring if the possible leakage-path over the surface is a long path, than if it is short.

In building commutators it is usual to assemble the bars to the proper number, with the interposed pieces of mica, clamping them temporarily around the outside with a strong iron clamp, or forcing them into an external steel ring by hydraulic pressure. They are then put into the lath and the interior cylindrical surface is bored out. Then the ends are



FIGS. 242 AND 243.—COMMUTATOR AND BRUSH-HOLDERS OF GÜLCHER CO'S 4-POLE MACHINE.

turned up, with the annular hollows to receive the clamping-pieces. The whole is then mounted, with proper insulation, upon the sleeve, and the end clamping-pieces are screwed up. It is then heated in a stove, and the end clamping-pieces are further tightened up. Lastly the temporary external clamps or rings are removed and the external surface is turned up true. The sleeve should be properly keyed or otherwise secured to the shaft, that there may be no slip between it and the armature to which it is afterward connected. Connection is made with the armature conductors by means of radial strips or wires of copper, which are inserted into a cut

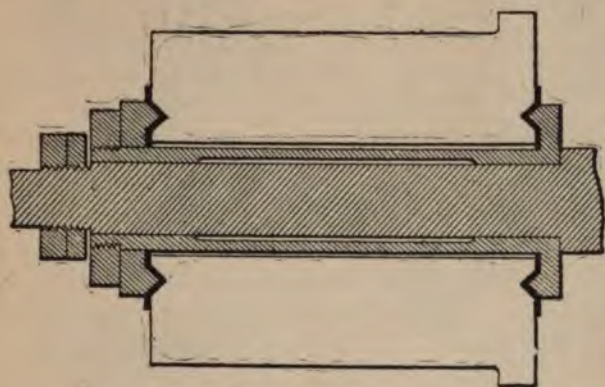


FIG. 244.—SECTION OF COMMUTATOR (GÜLCHER Co.).

sawn in the corner of each bar, and firmly held there. A good mode is to rivet the strip connectors into the corners of the bars before they are assembled, each riveted joint being also sweated in with solder. Fig. 245 shows a simple mode of doing this; while Fig. 246 shows commutator bars formed with a lug to receive the rivet *r*. In this example the nick *h* is to prevent the brushes from being set too near to the radial strips.

It is important that these connecting strips should be properly attached, since they are subjected to considerable mechanical forces. Twice in each revolution each such strip carries a strong current; and, owing to the existence of a

stray magnetic field, is consequently racked toward one side. Before this was understood it gave rise to frequent accidents.

In some large recent machines there is no separate commutator; the brushes trailing against some part of the copper conductors of the armature winding themselves. This is the case with the great Siemens dynamos at Berlin (Plate VIII., and Fig. 229, p. 302).

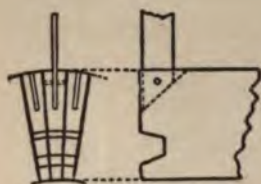


FIG. 245.—ATTACHMENT OF
RADIAL CONNECTOR.

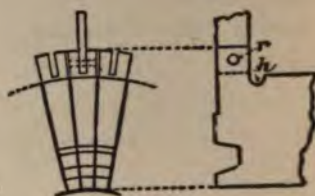


FIG. 246.—ATTACHMENT OF
RADIAL CONNECTOR.

Brushes.—The kind of brush most frequently used for receiving the currents from the collector, consists of woven copper wire gauze folded on itself and compressed as shown in Fig. 247, *e*. It was introduced about twelve years ago by Mr. A. P. Trotter. In order to prevent fraying at the edge it is usual to fold the gauze obliquely, as in Fig. 247, *f*. Sometimes the core of this gauze is made of exceedingly fine copper wires either straight or in soft plaited strands. The earliest sort of brush used consisted of a quantity of straight copper wires laid side by side, soldered together at one end, and held in a suitable clamp. Two layers of wires were often thus united in a single brush, as shown in Fig. 247 *a*. The object of all these devices was to secure a contact at a large number of points.

Brushes are also made of broad strips of springy copper slit for a short distance so as to touch at several points Fig. 247, *b*. Such are used in the Brush and Thomson-Houston arc-light dynamos. This kind of brush is usually set tangentially to the surface of the commutator, not sloping to it at an angle as is the case with the thicker kinds of brushes.

Edison has used as brushes a number of copper strips placed edgewise to the collector, and soldered flat against one another at the end furthest from the collector, Fig. 247, *c*. In some machines, a compound brush made up alternately of layers of wire, like Fig. 247, *a*, and split strips of copper, like Fig. 247, *c*, has been adopted.

Other makers have used a number of very thin copper strips laid over one another as in Fig. 247 *d*, held together in a suitable clamp.

Rotating brushes in the form of metal rollers or disks have been repeatedly tried, but are not successful.

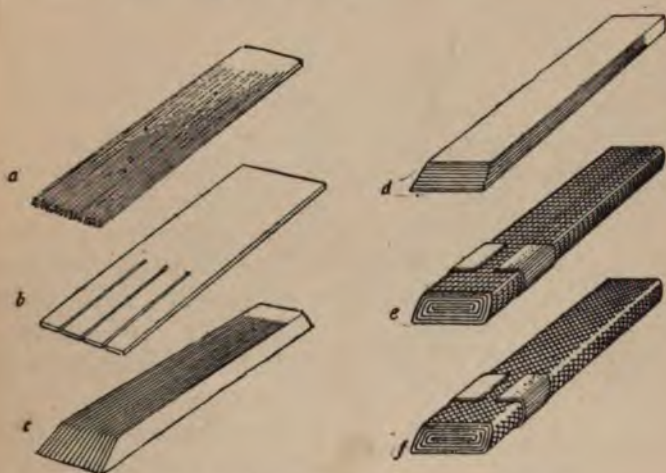


FIG. 247.—DIFFERENT KINDS OF BRUSHES.

It was suggested¹ by Professor G. Forbes to replace the brush by a slab of fine-grained and good conducting carbon. Carbon brushes are indeed used now frequently, both for dynamos and for motors. It is usual to provide a cross-section of about 1 square inch for each 50 amperes; but a really good conducting carbon will carry double this. They wear the commutator less than copper brushes, and facilitate sparkless collection: but they are more liable to heat, and need larger commutators.

¹ Specification of Patent 1288 of 1885.

It is usual, for all but the very smallest machines, to place at least two brushes side by side (as in Fig. 250, p. 323), instead of one broad brush. This allows of either brush being removed for trimming and replaced while the machine is running. It also tends to equalize the wear of the commutator, each brush being separately pressed against the surface; and the gap between two brushes can be covered by a brush at the other side. No rule can be given for the number or breadth of brushes that will apply to all cases. Some makers reckon an additional inch breadth of brush from each hundred amperes of output. Nor is it easy to give a general rule for the thickness of brushes.

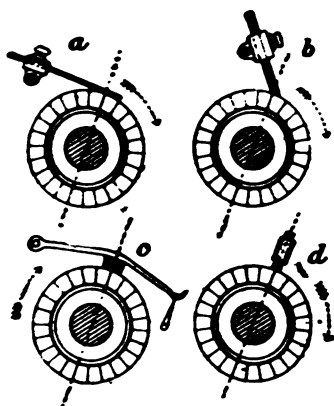


FIG. 248.—VARIOUS COLLECTING BRUSHES.

A thickness that will bridge the film of insulation between bar and bar is not sufficient, for each section of the winding requires to be short-circuited for a certain brief time, in order that the current in it may be reversed. The minimum thickness of brush (or breadth of its oblique end) seems to be about $1\frac{1}{2}$ times the thickness of the commutator bar. There is no objection to a greater thickness in those dynamos that have a large neutral zone about the neutral

point; or in which the curve of induction (Fig. 66, p. 78) has a broad flat top. But when a brush of great thickness is used another effect arises, namely, a waste in heating owing to the difference of potential between the parts of the commutator respectively in contact with the advance edge and hinder edge of the brush. To reduce this effect it has been proposed to use two thin brushes, one in front of the other, instead of single thick one, with a certain amount of resistance between them.

For armatures with duplex and triplex windings (p. 272) wider brushes must necessarily be used.

The angle at which brushes are set to bear upon the commutator varies with the construction. As a rule the brush is set sloping at an angle, the tip of the brush being raked in the direction of the rotation, so that it may not trip on the edges of the commutator-bars. In Fig. 248, *a*, is shown the case of a brush such as Fig. 247, *b*, set tangentially, as in arc-light machines. In Fig. 248, *b*, is a thick brush with bevelled end set at about 45° , as in most constant-voltage dynamos. Fig. 248, *c*, shows a form of brush devised by Holroyd Smith for use in motors, permitting of reversal of

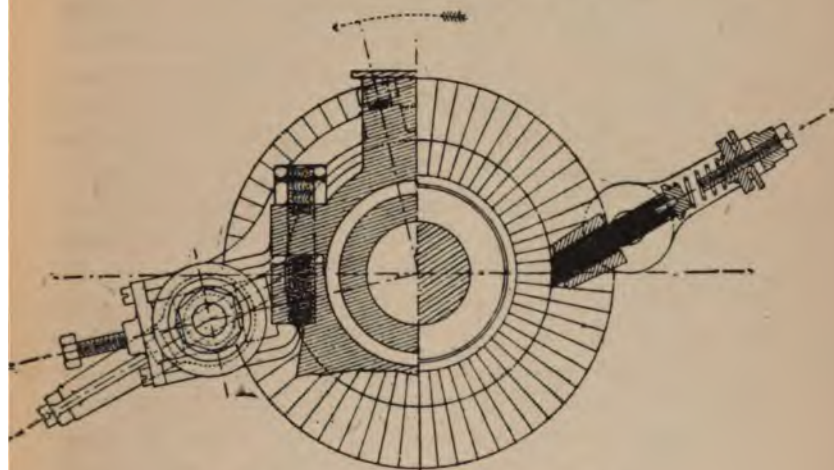


FIG. 249.—CARBON BRUSH-HOLDER (SNELL).

direction. Blocks of copper or gun-metal are attached to levers furnished with rubber bands to afford contact-pressure. In Fig. 248, *d*, is shown a carbon brush also adapted for use in reversing motors; the brush, a rectangular block of carbon, being pressed radially through a metal slide against the commutator.

In many cases where carbon brushes are used they are set to rake in a direction opposite to the rotation, so that the end-pressure may be greater when running. Fig. 249 illustrates a carbon brush-holder for use in mining motors.

Brush-holders and Rockers.—The mechanism for holding the brushes must fulfil the following conditions:—

1. The brushes must be held firmly, and joined with a good metallic contact to their circuit.
2. Brush-holders must permit brushes to be withdrawn or set forward as required.
3. Brushes must be held to make contact at proper angle to the surface of the commutator.
4. Brushes must bear with proper pressure upon the commutator; if too light, they will jump and spark; if too heavy, they will cut the commutator into ribs.
5. Brush-holders must permit brushes to be raised from contact.
6. They must also permit, by a proper mechanical action, of the brushes being held raised out of contact.
7. Insulated handles should be provided for all dynamos working above 100 volts, so that the brushes may be raised and adjusted without risk of shocks.
8. The insulation of the brush, or of brush and brush-holder together, must be very thorough.

A characteristic example of brush-holders is afforded by those of the Hilmer Company's machine. This is a 4-pole machine, or semi-connected, and therefore the two brushes must make contact at two points 90° apart. A kindred example, designed by Mr. Mountain for the "Tyne" dynamo, is given in Fig. 250, which also shows the construction of the commutator and the rocker. The rocker R consists of an iron ring in two parts, which is clamped together by bolts upon a fixed rim on the bearing. To this rocker are attached a handle H for shifting it so as to bring the brushes to the neutral point, and a couple of projecting lugs L (one only shown) to carry the brush-holder rods M. The latter are mechanically secured to the rocker lugs by screw nuts which hold them tightly; but they are electrically kept from making contact with the rocker by the interposition of an insulating bush and washers of ebonite. Upon the rods M are placed the brushes A which can turn hinge-wise upon them. Between the ends of A is fixed, by a screw F, a middle piece D with a

provided for the purpose. The brush is pressed forward by a compressed spiral spring, the force of which can be regulated by a screw through the projecting tail of D; whilst it can be held off by means of the catch K, which can be pulled back and slipped into a cleft on the end of D. In Fig. 243, p. 316, which depicts the similar mechanism of the Gülcher dynamo, one of the hold-off catches is caught in the cleft.

The rocker and brush holders of the Kapp 2-pole dynamo are shown in detail in Plate III. Here the mode of insulating

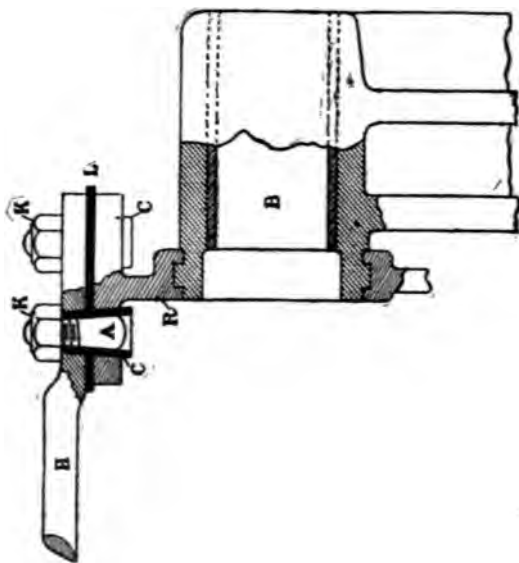


FIG. 251.—INSULATED BRUSH-HOLDER ROD (BARLEY AND STEVENSON).

is the same, but the current is led into a thick washer G; the contract-pressure is produced by an extended spiral spring stretched between a lug on the holder A and the fixed tail D; and the hold-off catch K is constituted by a straight spring which engages in a notch on the corner of A and is released by pressing up the piece Q, which is made of hard fibre. P is a pointer for setting the brushes to the right position in the holder.

A defect in the method of insulating by means of a bush

upon the brush-holder rod, is its liability to permit the rod to turn. A more solid construction is that of Fig. 251, in which the flattened end of the holder-rod H is clamped to an expansion of the rocker R by means of two conical bolts A; insulation being secured by an interposed layer L, and two conical bushes C of ebonite or fibre.

An excellent form of brush-holder, which permits the brushes to be fed forward longitudinally by a screw motion as required, has been devised by Messrs. Goolden & Co., and has a cam-motion for holding off.

Various inventors have tried to simplify the construction;

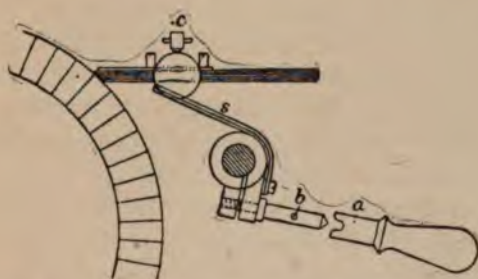


FIG. 252.—SIEMENS AND HALSKE'S BRUSH-HOLDER.

amongst them, Parsons has proposed to substitute weights for springs to give the requisite pressure.

A very simple and effective form of brush-holder, introduced by Siemens and Halske, is used largely in Germany. In this form, Fig. 252, the clamp which holds the brush is set on the end of a curved support made of several thicknesses of springy sheet brass. This is simply clamped to the holder-rod by a clamp screw which admits of the holder being shifted along the rod, or of being turned to give greater or less pressure. The tool is used for any of the required adjustments. These brushes are used with the large multipolar dynamos, such as that figured in Plate VIII., in which the second figure shows the star-shaped rocker which carries the brush-holders.

BRUSHES AND COLLECTORS FOR ALTERNATORS.

Alternators are no commutators, but they usually need special collecting contacts to convey the currents to and from the external circuit. The usual device is a pair of contact rings or slip-rings mounted on insulating hubs on the shaft with one or more brushes to press in each contact-ring. In most alternators in which the revolving part is the armature, great care must be taken to insulate well the two rings from each other and from the shaft. A deep projecting rim of concrete should be provided between the two rings if they are located on the same side of the machine, as in the Westinghouse alternator, Fig. 571, or the Hopkinson alternator, Fig. 411. In some alternators, the contact rings are on opposite sides of the armature, so that not only is better insulation given, but the risk of accidental shock is lessened. Two brushes are usually applied to each ring, so as to admit of replacement while running.

In those alternators in which the revolving part is the field-magnet, contact rings and brushes are needed to bring in the exciting current. But as the current is small and at low voltage, the collecting arrangements are simple and need no special care in insulation. In the slow-speed 3-phase alternators designed by Brown, Fig. 421, the exciting current is conveyed in through two belts of flexible stranded wire running over pin-metal pulleys.

CHAPTER XV.

MECHANICAL POINTS IN DESIGN AND CONSTRUCTION.

IN Chapter XIII. are considered the mechanical modes of transmitting the power from the shaft to the armature conductors and *vice versâ*. The design of dynamo shafts, journals, bearings, pedestals and pulleys is a matter equally requiring a knowledge of mechanical principles and practice. Such standard works as Unwin's *Machine Design* should be followed. Nevertheless there are some points in which the ordinary engineering rules cease to be entirely applicable; and it is because of this circumstance that it seems desirable to give the information embodied in the present chapter.

Pressure on Bearings.—In addition to the ordinary pressures on bearings, due to weight of the shaft and its attachments, and to the lateral drag of the driving-belt, there is in dynamo-machines a third cause producing pressure, namely the actual magnetic pull which the field-magnets exert on the armature core. This is notably great in the case of dynamos having a single magnetic circuit. An example in which the field-magnet tends to lift the armature is afforded by those machines, such as the Edison-Hopkinson, Fig. 287, p. 422, in which the magnet stands over the armature; whilst contrary examples are furnished by machines in which the armature is above the field-magnets, as in the Kapp dynamo, Plate I. and Fig. 259. If the armature is perfectly centred there will always be a tendency to drag it in such a way as to make the entire magnetic circuit more compact. This can be partially obviated by placing it eccentrically, slightly below the centre of the bored polar faces in machines of the under-type, and slightly above the centre in the over-type. In Kapp's machine the downward

machine design. It is usually assumed that journals are made larger for higher speeds, because of the necessity of getting rid, by the greater cooling surface, of the heat generated at the higher speed. But it is known that this assumption leads to the rule

$$l = F n \div \beta;$$

where l is length in inches; F the force (in lbs.) on the bearing; n the number of revolutions per minute; and β a constant which, according to various authorities, may vary between 66,000 and 1,000,000. With such a variation, the rule is almost useless as a guide to design; moreover it takes no account of the diameter of the journal. In all good engineering practice the ratio between the diameter and length of a journal bears a relation to the speed. For slow speeds, such as 100 revolutions per minute, the length need be no greater than one diameter; whereas for speeds of 1000 and upwards the length is five or six diameters, and in high-speed fans sometimes as much as eight diameters.

From this we get the approximate rule:—

$$l/d = 1 + 0.004 n.$$

The rule given above, which is an ordinary one for mill-shafting, is known not to apply to crank-shaft bearings, where centrifugal force is of little importance, but where there come heavy alternately-directed thrusts and wrenches. Still less can it strictly apply to dynamo machines. In these, for the most part, the power is transmitted through a few inches of shaft from a pulley to the armature. The journal between these two parts, if the pulley is outside, is obviously sustaining a much severer wrench than the journal at the other end; it is in many dynamos made larger and longer than that at the commutator end.

In the table on the next page are given data of sundry machines.

The safe diameter for a journal to give requisite strength depends on the load tending to bend it, as well as on the mere twisting-moment that results from the power transmitted

through it. The diameter of a shaft is usually calculated from the formula, applicable when there is no bending:—

$$d \text{ (inches)} = c \sqrt[3]{\text{HP} \div \text{revolutions per minute}};$$

where $c = 2.9$ for steel shafts.

The lateral loading of an overhung pulley, due to the belt, produces a considerable amount of bending. Taking the ratios of breadth of pulley to diameter which are usual in dynamo manufacture, it will be found that c ought to be taken as having a value variously estimated from 4.2 to 5.5.

Again, the spindle or shaft of a dynamo is subjected to bending by the weight of the armature, by the magnetic drag

TABLE OF JOURNAL SIZES.

Dynamo and Description of Armature.	Revolutions per minute.	Distance between bearings (inches).	Output (kilowatts).	Length (inches).	Diameter (inches).	Ratio l/d .
Edison (bipolar standard type)	3100	18.08	1	2.62	0.625	4.7
	1600	34.75	10	6.75	1.5	4.2
Slow speed multipolar ring	..	..	100	15.75	4.1	3.8
	..	..	1000	36.	15	2.4
"Manchester" (ring) (1887)	1600	26	4.5	3.75	1.4	2.68
Ferranti alternator (star-disk) (1883)	1700	28	7.5	9	1.5	6
				5.25	1.25	4.5
Kapp	780	34	22.5	10	2.25	4.4
				8.5	2.25	3.77
Brown	200	44	100	14	3.5	4
Brown continuous current (1890)	500	56	26	9.75	2.0	4.88
				9.75	2.5	3.9
Ferranti alternator (1889)	120	85	1000	57	14	4
Mordey alternator (Field-magnet revolving)	500	53.75	75	13	4.5	2.88
				13	4	3.25
Mordey (1894)	150	100	800	45	11.5	4
Parsons Turbo-alternator	3000	..	350	12	2.3	5.2

on its core, and in belt-driven machines by the lateral drag of the pulley. When running, it is also subjected to bending stresses if the masses it carries are not properly balanced. If the brasses of the bearings keep the journals in line, it is evident that all such actions tend to bend the shaft at definite points. In machines with discoidal armatures a greater length of shaft is free to bend than in those with drum and cylindrical ring-armatures, which stiffen the middle portion. Professor Perry calculates for discoidal armatures,

$$l/d = n \sqrt{L} \div 1000;$$

and for drum- and elongated ring-armatures,

$$l/d = (n \sqrt{L} \div 3500) + 2,$$

where L is the length of the shaft between the middle points of its bearings, in inches; and n , l and d as before.

Journals, if plain, are usually terminated by collars or raised shoulders, to bear against the brasses and limit end-play. In some forms of machine end-play is specially provided for, so as to cause an even wear at the commutator.

In some British machines, chiefly small ones, and others of American make, a shaft of the same diameter throughout is used, with collars shrunk on to prevent end-play. This is not good engineering. A shaft ought to be as thoroughly designed for its work as any other part of the machine. It is well recognized in machine design that where an axle has to bear a transverse load tending to bend it between the points of support, it must be thickest where the bending moment is greatest. One takes as a basis of calculation the diameter appropriate at the journals (found as above) and assuming that the shaft is of circular section, calculates the diameters at the other parts by the rule that the diameter at each point should be proportional to the cube root of the bending moment at that point.¹ It must not be forgotten that where key-ways are to be subsequently cut for securing the spiders or other attachments, additional diameter must be given to admit of this without reduction of strength. An example of an excellent

¹ See Unwin's *Machine Design*, 147.

part of design is afforded by the shaft of Brown's dynamo, Plate IV.; also by those of Kapp's dynamo, Plate II.; and of Murray's dynamo, Fig. 284.

In the first of these examples it will be observed how the armature spiders fit in over the middle portion of the shaft, and the whole is tightened up by a threaded nut against a collar in the shaft. The commutator is built up around another and shorter sleeve which slips over a slightly recessed part of the shaft on the other side of the collar. The pulley is within the bearing, not overhung.

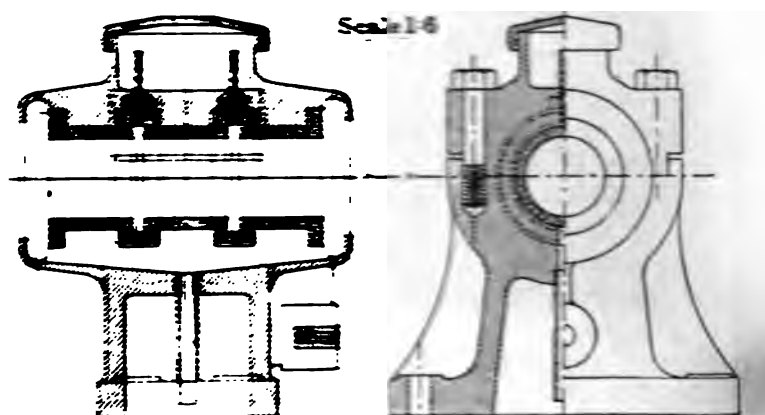


FIG. 253.—THRUST BEARING OF KAPP ALTERNATOR.

In the second, the armature spider is a long sleeve of cast iron, which stiffens the middle portion of the shaft, and is held up by a threaded nut against a collar.

Bearings and Pedestals.—Bearings for dynamos are always made divided, so that the armature can be lifted from its bed, and usually with steps of brass or gun-metal seated in an appropriate pedestal. Those who are not familiar with this elementary part of machine design should examine the drawings of the pedestals and bearings of various machines; particularly those of the Kapp dynamo, Plate I.; and those of late XVIII. and Figs. 273 and 277. Often the pedestal is

made in two parts bolted together; the joint occurring at the level of the under side of the armature to admit of the latter being withdrawn, and affording a resting point during removal. Where long bearings are used they are occasionally made of cast iron instead of gun-metal or brass. More often a soft metal bearing is used; or rather a soft alloy, such as Babbitt's metal or "Magnolia" metal, is used as a lining for a step of gun-metal or cast iron; such antifriction metal being cast into shallow recesses formed for that purpose in the hollow of the step.

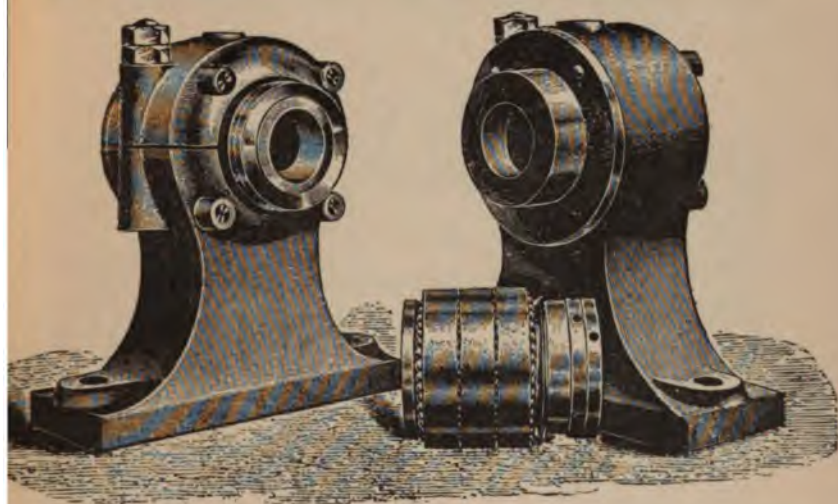


FIG. 254.—BALL BEARING (AUTO MACHINERY COMPANY).

Ball Bearings.—With the introduction of machinery of precision for making steel balls for antifriction bearings, the use of the latter for dynamos has been coming into favor. Fig. 254 gives a view of a bearing of this class, and shows the disposition of the balls between the revolving liner and the outer stationary rings. For motor-generators, where there is no lateral drag due to belts, these bearings have been found excellent.

Thrust Bearings.—In all dynamos with disk or discoidal ring-armatures, end-play is inadmissible; and thrust-bearings

must be provided similar to those used on screw propeller shafts with raised collars on the journals. Or, instead, the shaft may be constructed with shoulders somewhat deeper than usual at the journals, to bear against the brasses. The reader should examine the various thrust-bearings in the drawings of the following dynamos; Mordey-Victoria, Fig. 283, p. 418; Ferranti alternator, Fig. 417,. That of the Kapp alternator, built by Messrs. Johnson and Phillips, is shown in Fig. 253.

Spherical Bearings.—With all long bearings it is of great importance that they should not only be exactly concentric,

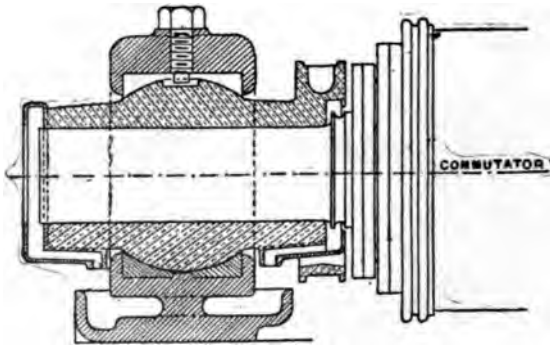


FIG. 255.—SPHERICAL BEARING OF GOOLDEN DYNAMO.

but that they should also be accurately in line. To permit the steps to adjust themselves to perfect alignment it is now a frequent practice to provide them with a spherical seat; that is to say, a spherical or nearly spherical shape is given to the enlarged central portion of the bearings, and this spherical portion is provided with a soft metal seat on the pedestal.¹ Fig. 255 gives a design by Mr. Ravenshaw. The bearings of the Westinghouse alternator closely resemble Fig. 255, but are adapted to longer journals.

Lubricators.—Provision must be made for lubricating

¹ See paper by Mr. Coleman Sellers, in *Journal of Franklin Institute* for 1872, or *Engineering*, xv. 17, or the figure in Unwin's *Machine Design*, p. 170.

bearings with a due supply of oil or grease, and arrangements to prevent waste and spilling. It is usual to provide an oil-well in the hollow casting of the pedestals, into which the oil drains from the ends of the brasses. Sight-feed lubricators which supply the oil visibly drop by drop are undoubtedly best for ordinary machines. Such a lubricator is illustrated in Fig. 256. The lever C at the top closes the feed of oil when the machine is not wanted to run. The collars A and B regulate the rate at which the oil flows down to drop through the tube sight below. For ship dynamos special forms that cannot spill oil are preferable. It is usual to provide a collar on the journals to collect and throw off the oil centrifugally, the lips of the bearing being carried (as shown in Fig. 255, above) beyond the brasses, and provide with a re-entrant rim which catches the oil and returns it to the well below. Sight-drain lubricators which permit the oil that flows from the bearings to drop visibly are in some cases preferable. For large dynamos, where there is great weight on the bearings, special precautions have to be taken, as in the lubrication of the bearings of propeller shafts. Oil is supplied under pressure, sometimes from two independent sources, to prevent risk of failure. Such arrangements are the more needful in the case of dynamos, because the motion is one of pure rotation, the shaft not being subjected, like the crankshaft of a steam engine, to alternate lateral thrusts, which help to work the oil in under the journals. Sellers has



FIG. 256.—VISIBLE DROP-FEED LUBRICATOR.

proposed a double lubrication¹ as a safeguard. The ordinary lubricator supplies oil at the centre of the bearing, and the top brass is provided near each end with a cup containing a stiff mixture of tallow and oil, which only melts in case the bearing heats from failure of the ordinary oil supply. Self-lubricating devices are sometimes used, an oil-well being provided in the lower brass, into which dips a collar on the journal, or a metal ring running loosely over it, or even a mere ring of felt. (See Brown's motor, Plate XVIII.) Fig 257 represents the self-oiling arrangement used in their small motors by the Crocker-Wheeler Co. of New Jersey. Some



FIG. 257.—BEARING WITH SELF-OILING RINGS.

makers provide spiral grooves in the soft-metal lining of the bearing, so that the oil brought up by the ring is distributed along the journal.

For dynamos and alternators of the "umbrella" type, with vertical shafts for use with turbines, very special oiling arrangements must be used on account of the very great weight on the bearings. (See Plates VI. and XVI.) Arrangements are made in all large machines of this type to take a large portion

of the dead weight off the bearing surfaces, by means of hydraulic floats, or in some cases by applying electromagnets to produce an upward pull. In the case of the great Niagara alternators, Fig. 432, the lubrication is effected by oil placed in a large cast-iron cup several feet in diameter attached to the shaft below the bearing. Into the oil dips a stationary tube, up which, when the cup revolves, the oil rushes to the top of the bearing. A cold-water circulation is provided for artificial cooling.

¹ Unwin's *Machine Design*, 171.

Keys and Feathers.—Keys for securing the armatures and pulley to the shaft should be of the sunk or flat type, not of the saddle type, which is less reliable. The rules for keys are as follows: b meaning breadth; t thickness; and d diameter of the eye of the hub, all in inches—

$$\begin{aligned} b &= \frac{1}{4}d + 1''; \\ t, \text{ for sunk keys} &= \frac{1}{10}d + \frac{1}{8}''; \\ t, \text{ for flat keys} &= \frac{1}{11}d + \frac{1}{16}''; \end{aligned}$$

Where two or more feathers are used on different sides of the shaft, the breadth of each may be somewhat less than this. For small machines these numbers are needlessly large.

Pulleys and Belts.—There is no need to give special rules for these, as the ordinary rules for running machinery apply.

Bed-plates.—In designing bed-plates it is usual to save weight of metal by coring out and leaving stiffening ribs and flanges. All this is quite right except in those cases where any part of the bed-plate serves also a magnetic purpose and constitutes a part of the magnetic circuit. For example, in the Kapp dynamo, Plate I., the bed-plate serves partially as a yoke for the field-magnet; and in the "Manchester" dynamo of Mather and Platt, Fig. 285, p. 421, as also in Brown's dynamo, Plate IV., the part of the casting which passes under the armature must be left solid. British makers usually design bed-plates of box-patterns. In the case of machines with drum or cylindrical-ring armatures it is convenient to be able to withdraw the armature longitudinally by removing one pedestal, which therefore should be a separate casting. In that case, for machines of the over-type, it is convenient that the pedestal should be made removable down to the level of the under side of the armature, so that when the upper part is removed the stump may form a convenient resting place for the armature in removal. A case is shown in Fig. 273, p. 401, and in the Kapp dynamo, Plate I.

Couplings.—When dynamos are driven without belting from the steam engine on the same bed-plate, it is frequent to

connect their respective shafts by a coupling. Of these devices there are several special patterns, such as Brotherhood's, with a connecting part of leather, and Raworth's with flexible steel bands, admitting of a certain amount of play if the two shafts are not in exact alignment. It is well to construct the coupling so that it also insulates the engine from the dynamo.

CHAPTER XVI.

ELEMENTS OF DYNAMO DESIGN: CALCULATION OF
CONTINUOUS-CURRENT DYNAMOS.

THE symbols used in this chapter are described on p. 169.

As in all designing of machines, so with the designing of dynamos, experience is the ultimate guide. Before we can begin to design a dynamo we must know what we want: how many amperes it is to give, and at what voltage. We must also have definite ideas as to the intended speed of running. To design a machine which, when driven at a prescribed speed, shall yield any desired number of amperes of current at any given voltage, is a very simple matter to an engineer who has already had experience in designing dynamos of the same general type, but of different output. To a man who has designed 2-pole continuous-current machines for incandescent lighting it is a simple matter to design another machine of the same sort. But it would be to him by no means so easy from his experience only to pass to designing machines of a multipolar type, or to design alternate-current machines.

Happily a vast quantity of data are available respecting good machines of many types and sizes. Tabulated statistics of the results of experience are invaluable to the designer. Foremost of such statistics are those to be found in a series of articles by Mr. Wiener in the *Electrical World*, in the years 1894 and 1895. Many points need no such data, but may be found from first principles.

It is known, for example, that the number of watts of output of a dynamo of given form, at a given speed, is approximately proportional to its weight. For example: given a dynamo which at 720 revolutions per minute yields (without sparking or overheating) 200 amperes at 105 volts (a 21 kilowatt machine), it is known that using the same iron

carcass, and rewinding the machine with new coils equal in weight to those previously used, the machine may be made to give (at same speed as before) 300 amperes at 70 volts, or 250 amperes at 84 volts, or 30 amperes at 700 volts—the products in each of these cases being 21,000 watts. A machine for double the output would have double the weight of iron and double the weight of copper, approximately, if of the same type.

Also, since the voltage is proportional to speed, if a new dynamo had to be designed to give the same output at a speed of 480 instead of 720 revolutions per minute, a carcass about $1\frac{1}{2}$ times as heavy would be required. A manufacturer who had in stock carcasses of various sizes would, of course, select the nearest size and wind it with an appropriate winding.

The first stage in understanding the subject is to examine carefully the design of some well-established machines, and to see how the dimensions of their several parts are adapted to their functions. It will then be an easier matter to work out any case for a fresh type of machine. But that we may know what sort of data are needed from experience, let us make a preliminary attempt at calculating a design. Calculations are needed to ascertain the proper sizes of the parts. Some of these calculations are purely electrical, other magnetic, others mechanical, and some are of a wholly empirical nature founded on experience. If a dynamo is to be constructed to give, say, an output of 200 amperes at 55 volts, the conditions respecting safety from overheating practically determine the size of wire that can be used for the prescribed current: no calculation being needed beyond a reference to a wire-table, and the knowledge that in armatures of dynamos it is usually quite safe to allow 2000 or more amperes to the square inch. Suppose we settled on a stranded wire of 7 No. 13 S.W.G., which will safely carry 100 amperes (each conductor carries only *half* the armature current). If, however, the field-magnet is shunt-wound, as it must be for ordinary lighting at constant pressure, there will be additional amperes to allow for besides the 200 for the lamps. Let it be taken that 5 amperes, or $2\frac{1}{2}$ per cent. of the current, will suffice. Suppose this all settled, then the question arises of the 55 volts. What size

of armature, what winding of it, what size of field-magnet will be required; and how must the latter be wound so as to give what is required at the proper speed? Again, it must be remembered that if 55 volts is to be the pressure at the mains, the armature must generate more volts than this—say 57 or 58—to allow a margin for the “lost” volts (p. 181). Suppose this settled, then what is the next step?

Consider the fundamental equation of the continuous-current dynamo (see pp. 46 and 171).

$$E = n Z N \div 10^8.$$

Now if we assume that the speed n is prescribed beforehand this formula tells us that the volts of the armature depend on Z , the number of armature conductors employed (i. e. on the weight of copper), and on N , the number of magnetic lines through the armature (i. e. on the cross-section of the iron core, and on the degree to which its magnetization is forced up). In the case in question, suppose the prescribed speed to be 1140 revolutions per minute, then n (the revolutions per second) = 19. And if E is taken at 57, it follows that $Z N$ multiplied together must come to 300,000,000. But how much must Z and N be separately? Well, experience shows that in such machines as this is to be, each armature-section should consist of one, or, at most, two turns, whether wound as ring or as drum. Experience also shows that for 2-pole machines it is convenient if the number of sections (and therefore of bars in the commutator) is a multiple of 6. Also experience shows that if there are fewer sections than 30 there will be fluctuations and possibly spark troubles, and that if there are so many as 150 or upward, there comes in great expense in the construction. We might take 42, or 48, or 54, or 60, or 72, and work out a design on any of these. It is very easy, on completing the calculations, to try another set if the first do not seem quite satisfactory. If there is only one convolution in each section, and the armature is ring wound, Z will be the same as the number of bars of the commutator; but if drum-winding is adopted, then Z will be numerically twice as great. Now if Z is small, N will be large,

and *vice versa*; and we know that to secure sparkless running it is well to keep N large and Z small (p. 95). Suppose, then, we take Z at 72, so that when wound drum-wise there will be 36 sections and a 36-bar commutator. Clearly this will involve that N shall equal $300,000,000 \div 72 = 4,166,600$; in round numbers there must be a flux of 4,170,000 magnetic lines through the core of the armature. Again, experience shows that the proper degree of magnetization to allow in armatures of such machines is (see p. 368) from 15,000 to 17,000 lines to the square centimetre, or say from about 90,000 to 100,000 lines to the square inch. To carry the 4,170,000 lines the armature core ought then to have a nett cross-section of about 45 square inches, or say, 288 square centimetres. But here again comes a choice. How shall we determine this cross-section? What size of core-disk shall we choose, and what total length of core-disks shall we pack together along the shaft? Shall we use a toothed, or a smooth core-disk? Suppose we decide to use smooth cores. If we take large core-disks of great radial depth we shall only need a comparatively small number of them, and our armature will be short; whereas if we take small core-disks we shall have a long armature. Here two other considerations come in to influence our decision. We have provisionally settled the gauge of copper conductor to carry one current—a stranded wire of 7 No. 13's, of which 3.38 turns will lie side by side in the breadth of an inch. If there are to be 72 such conductors all in one layer, they will occupy about 21 inches side by side. If we allow nothing extra for inserting driving-horns, this will involve core-disks about 7 inches in external diameter. If we say $7\frac{1}{4}$ inches with a $4\frac{1}{4}$ -inch hole, the doubled radial depth of iron will be 3 inches; and as there are to be 45 square inches of section of iron that will require a total length of about 15 inches, or, with the insulation between the core-disks a length of 16 inches, the core of the drum will then be about twice as long as its own diameter. It is usual in drum-cores to make the length a little greater than the diameter; but this will do for present purposes. But there is another consideration. If we have got so many complete convolutions of

conductor as 36, and each conductor carries $102\frac{1}{2}$ amperes, there will be for total cross-magnetizing effect a product of 3690 ampere-turns. Will this, on the core-disk of $7\frac{1}{4}$ inches diameter be too great—that is to say, so great as to cause sparking? This is purely a question for experience to decide (see p. 385). Now experience shows that in 2-pole drum-wound machines a core-disk $7\frac{1}{4}$ inches in diameter will carry at least 5200 ampere-turns without sparking, so that we are well within the limit of sparklessness. We might diminish internal resistances a little by choosing a smaller core-disk, so as to make a longer core that will waste less wire in wrapping across the ends; but in that case we cannot use the stranded wire first selected. If, for example, we choose 6-inch core-



FIG. 258a.

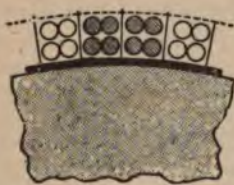


FIG. 258b.



FIG. 258c.

disks with 2-inch holes, we should require a nett length of 12 inches, or a gross length of nearly 13 inches. And we could not fit the 72 conductors around the periphery unless these are specially made, say of drawn copper strips placed three side by side (as in Fig. 258a), each strip being in section 250 mils wide by 60 mils thick. The three overspun together would be about 210 mils thick; and the seventy-two would occupy about 15 inches around the periphery of the 6-inch disk, leaving 3.8 inch for the insertion of driving-horns. Another way of winding would be to use, with $7\frac{1}{2}$ -inch core-disks, four wires in parallel, instead of the stranded conductor, each wire being a No. 10 S.W. G., carrying 25 amperes, arranged two deep, there being 144 around the periphery, and occupying about 22 inches side by side, as in Fig. 258b; a third method would be to use a toothed core-disk $8\frac{3}{16}$ inches in diameter, with 72 teeth, with wires of rectangular section

[illegible]

of the iron limbs. Having done this, see whether, without mechanical difficulty or risk of overheating, the quantity of wire thus calculated can be wound upon the length of limb so assumed; and having made this comparison, then diminish or increase the length chosen for the limb, and recalculate. But here again comes in a complexity. If we assume that the armature has no demagnetizing reaction, we shall find our calculated quantity of wire much below the quantity actually required. Therefore, calculate approximately by the rule given on p. 231 the number of demagnetizing ampere-turns, and add 2.0 times this to the number previously found; for the field-magnet must be made long enough to carry this additional number of coils. In the case under consideration assume the polar angle to be 145° on each side, it follows that $\frac{145}{180}$ of 72, or about 58 of the conductors of the armature, will be in the gap-spaces at any one moment, and that there will be a belt of conductors (see Fig. 70, p. 85), seven broad, exposed between the tips of the poles. This gives us 700 ampere-turns of demagnetizing power if the brushes are assumed to be set near the pole-tips.

Now the external diameter of the armature is $8\frac{1}{2}$ inches, and we must allow $\frac{1}{8}$ inch clearance all round, making the diameter of the bored polar surface $8\frac{1}{4}$ inches, and the actual gap-space from iron to iron $\frac{1}{2}$ inch. The gap-spaces themselves may be taken as being $10\frac{3}{4}$ inches along the curve, and 15 inches from back to front. We are now ready for the rules by which to calculate the field-magnet design. Hence we may pause here in these general considerations, which have been followed far enough to show the need for handy formulæ of sufficient exactness.

ELECTRICAL CALCULATIONS.

§ 1. *To calculate the Lost Volts in the Armature.*—Take the number of amperes C_a flowing through the armature; multiply this by the number of ohms (or fraction of an ohm) that represents the internal resistance of the armature.

$$\text{Lost volts} = r_a \times C_a.$$

A similar mode is to be used for calculating the volts lost by resistance in any coil in series with the armature. If the other internal main-circuit resistances, such as a series coil, are called r_s , we must add this to r_a and get

$$\text{Lost volts} = r_s + r_a \times C_a$$

§ 2. *To calculate the Current going through Shunt.*—Divide volts e at terminals by number of ohms of resistance r_s of shunt coil.

$$C_s = e \div r_s$$

In a good modern machine C_s may be taken as about 20 to 15 per cent. of C in machines of less than 1 kilowatt; 10 to 5 per cent. in machines of 1 to 10 kilowatts; 5 to 2½ per cent. up to 200 kilowatts; 1½ per cent. in machines of 1000 kilowatts (or less).

§ 3. *To calculate the Whole Current flowing through Armature.*—Add to the number of amperes C that flow to the lamps, the number of amperes C_s flowing around the shunt coil.

$$C_1 = C + C_s$$

Or a percentage as above may be added to the current to be supplied to the mains.

§ 4. *To find the Gauge of Wire needful for the Armature.*—Remembering that there are in bipolar machines two paths through the armature, divide C_1 by 2, and then refer to the *Amperage and Wire-Gauge Table*, Appendix A, and select a wire if it is to be a wire winding; otherwise a stranded bar will be chosen. Remember that in very small machines it is safe to go up to 4000 amperes per square inch, and in large machines to 2000 amperes per square inch.

§ 5. *To find the Whole Electromotive-force E that must be generated in the Armature of a Dynamo.*—Ascertain the number of volts of pressure e , at which the mains are to be supplied from the terminals of the dynamo (depending on the lamps that are to be used); to this add the calculated number of *lost volts*.

$$E = e + r_a C_a$$

§ 6. *To calculate the number of Armature Conductors Z.*—This matter of experience; see p. 313 above, and p. 342.

7. *To calculate the Electromotive-force in the Armature. (Continuous Current Machines.)*—Multiply together the revolu-

tions per second n , the number of armature conductors Z , and the magnetic flux N , then divide by one hundred million. For:—

1 volt = 10^8 C.G.S. units of electromotive-force.

$$E \text{ (volts)} = \frac{n Z N}{10^8}$$

[Example: a certain Phoenix dynamo. $n = 23.6$; $Z = 180$; $N = 2,530,000$. Find E .] For multipolar machines one must also divide by the number of bifurcations of circuit. For armatures not internally cross-connected this will be half the number of brushes (see p. 257).

EFFICIENCY CALCULATIONS.

§ 8. *To calculate the Wasted Power in a Dynamo.*—To calculate horse-power from the watts divide the number of watts by 746.

(1) Watts wasted in armature coil. Multiply volts lost in armature by amperes in armature; or multiply resistance of armature by square of armature current.

(2) Watts wasted in series coil. Multiply volts lost in series coil by amperes in that coil; or multiply resistance of coil by square of amperes in that coil.

(3) Watts wasted in shunt coil. Multiply amperes in shunt by volts at terminals of shunt; or divide square of volts at terminals by resistance of shunt coil.

(4) Watts wasted by eddy currents not calculable directly.

(5) Watts wasted by magnetic hysteresis. The formula and table of hysteretic constants given on p. 140 will give the number of watts wasted by hysteresis in well-laminated soft-wrought iron, when subjected to a succession of cycles of magnetization as in the rotating armature core of a dynamo.

§ 9. *To calculate the Electrical Efficiency.*—Multiply together the useful current C and available volts e , and so obtain the useful watts. Multiply together the total current C_a and total electromotive-force E , and so obtain the total watts of gross output. The electrical efficiency is the ratio of the former to the latter.

$$\eta = e C \div E C_a$$

Or it may be calculated by dividing the useful watts by the total watts (useful and wasted added together). The electrical efficiency does not include waste by eddy currents, hysteresis, or friction.

§ 10. *To ascertain the Commercial Efficiency.*—Calculate by

rules given on pp. 137 and 138 probable losses by hysteresis and eddy-currents in iron; and estimate losses by friction at bearings and by eddy-currents in copper from data of tests of machines of similar type. Then divide useful watts by total watts including these losses.

MAGNETIC CALCULATIONS.

§ 11. *To calculate the Magnetic Flux through the Armature.*—Measure e , add lost volts, and so calculate E ; then multiply by 10^8 and divide by n and by Z .

$$N = \frac{E \times 10^8}{n \times Z}.$$

[Example: An Edison-Hopkinson dynamo. $n = 12.5$; $Z = 80$; $e = 105$; $r_a i_a = 3.26$; find N .]

§ 12. *To calculate the Magnetic Flux-density B in an Iron Core.*—Ascertain the magnetic flux N through that core; and the nett cross-section A , of iron in that core. Then divide N by A .

$$B = N \div A;$$

or, if measures are given in square inches,

$$B_{..} = N \div A''.$$

[Example: in an Edison-Hopkinson dynamo N in armature = 10,826,000; $A'' = 125$ square inch; find $B_{..}$.]

[Example: in a Kapp dynamo N in armature = 6,730,000; $A = 403.1$ square centimetres; find B .]

§ 13. *To calculate the Cross-Section of Iron to carry a given number of Magnetic Lines.*—First determine how many is the total number of magnetic lines that must pass through the armature core when machine is at full work: call this N . Next, settle what is the advisable value to give to the flux-density B . In continuous current machines for incandescent lighting it is not usually advisable to push the magnetization further than $B = 17,000$ (to the square centimetre), or $B_{..} = 100,000$ (to the square inch). For arc-lighting machines the flux-density may be pushed further. For alternate-current machines a much lower density is desirable: B say = 7000. For cores of transformers a density of 2000 to 4000 is usual. Having settled the value of B or $B_{..}$, dividing N by the value settled will give the required sectional area A or A'' .

[Example: in a certain Phoenix dynamo it was decided that $B_{..}$

should be 115,000 lines per square inch, and N had to be 2,606,000; find A'' .]

[Example: in a Kapp alternator, A in the armature core was 103.2 square centimetres; assuming $B = 6500$; calculate N .]

For calculating the requisite cross-section of field-magnets a similar process is used, but allowance must be made for carrying a larger number of magnetic lines (because of magnetic leakage); and it is advisable to use, even with wrought-iron cores, a somewhat lower degree of magnetization. If cast-iron cores are used, the section will have to be nearly twice as great, as it is not advisable in that material to force in more than about 8000 lines to the square centimetre, or than about 50,000 to the square inch.

§ 14. *To allow for Magnetic Leakage.*—In consequence of magnetic leakage the magnetic flux is different at different parts of the magnetic circuit.

[Example: in an Edison-Hopkinson dynamo it was found that to get 10,826,000 lines through the armature, enough magnetizing power had to be put on to make 14,289,000 lines flow through the field-magnet, 3,464,000 of these leaking away and not going through the armature. This is as if out of every 132 lines in field-magnet, 100 only were useful and 32 wasted.]

The symbol for the coefficient of allowance for leakage is v . Its value varies in different dynamos from 1.2 to 2 or more. In the example above given $v = 1.32$. Allowance must be made for v times N magnetic lines in the field-magnet in order that there shall be a flux of N lines through the armature. (Compare p. 151.)

§ 15. *To find the Permeability of Iron at any stage.*—Refer to tables or curves (such as those given on pp. 125 and 138) relating to the particular brand of iron under consideration.

[Example: in armature of Kapp dynamo, when running on open circuit $N = 6,730,000$; $A = 403.1$ square centimetres; find B ; and from this, assuming the curve for the iron to be the same as the uppermost curve in Fig. 85, find μ . Also find B and μ , when, at full load, N is increased up to 7,170,000 by the added magnetizing action of the series coil.]

[Example: in field-magnet (cast iron) of a Phoenix dynamo $A'' = 62$ square inches; N in armature = 2,606,000; v (leakage allowance coefficient) = 1.36. Calculate vN , then B_v ; then find μ by reference to Table II., p. 126, for cast iron.)

MAGNETIC RELUCTANCE: MAGNETIC CIRCUIT.

Fundamental Law of Magnetic Circuit.

Magnetomotive-force — **magnetic reluctance** = the magnetic flux in magnetic lines —

i. e. **The amount of the magnetomotive-force requisite to force a given number of Magnetic Lines through a Definite Magnetic Reluctance** — **Equals** the number which represents the magnetic reluctance of the circuit of magnetic lines that are to be forced through it. The product will be the amount of the magnetomotive-force.

If the magnetic reluctance has been expressed on the basis of **unitmotive magnetomotive force**, the magnetomotive-force, calculated in this way will require to be divided by 1.257, i. e. by $4\pi \div 10$ to give the number of ampere-turns of requisite magnetizing power.

a. **To calculate Reluctance of an iron core.**

a. **If dimensions are given in inches.**—Magnetic reluctance being directly proportional to length, and inversely proportional to sectional area, and to permeability, the following is the formula:—

$$\text{Reluctance} = \frac{l}{A \mu};$$

but the value of μ must be inserted until it has been calculated from $\frac{B}{H}$ as above in § 17.

b. **If dimensions are given in feet.**—In this case we apply a numerical coefficient which takes into account the change of units for permeability of the inch, and also, at the same time includes the operation of finding the magnetomotive-force by $H = \frac{NI}{10}$, where N is number of ampere-turns. So the rule to find the product is two-fold.—Divide the length (in inches) by the area in square inches, and by the permeability (formed as above from $\frac{B}{H}$) and then multiply by .5132. Or in symbols:—

$$\text{Ampere-turns per line} = \frac{l}{A \mu} \times 0.5132.$$

[Example: find the magnetic reluctance from end to end of a bar of wrought iron 12 inches long, with a cross-section of 4 square inches, on the supposition that the magnetic flux (N) ought to be amount to 44,000 lines.]

18. **To calculate the Total Magnetic Reluctance of the Magnetic wit of a Dynamo.**—This is done by calculating the magnetic reluctances of the separate parts and adding them together. Account

must, however, be taken of magnetic leakages by allowing for v N lines in the field-magnet cores and yoke.

In the simplest case the magnetic circuit consists of three parts: (1) iron in armature core; (2) air, copper, cotton, &c., in gap-spaces; (3) iron in field-magnet. The permeability of the materials in the gap-spaces may be taken as = 1. Hence the three reluctances in question are respectively written:—

	For centimetre measure.	For inch measure.
1. Armature. . .	$\frac{l_1}{A_1 \mu_1}$	$\frac{l''_1}{A''_1 \mu_1} \times 0.3132$
2. The Gap-spaces	$\frac{2l_2}{A_2 \mu_2}$	$\frac{2l''_2}{A''_2 \mu_2} \times 0.3132$
3. Magnet core ..	$\frac{l_3}{A_3 \mu_3}$	$\frac{l''_3}{A''_3 \mu_3} \times 0.3132$

19. *To calculate the Ampere-turns of Magnetizing Power Requisite to Force the Desired Magnetic Flux through the Reluctances of the Magnetic Circuit.*

(a) *If the dimensions have been given in centimetres, the rule is:—*

Ampere-turns = magnetic flux multiplied by the magnetic reluctance, divided by $\frac{1}{\pi}$ of π (= 1.257);

or, in detail, the three separate amounts of ampere-turns required for the three principal magnetic reluctances of a dynamo are expressed as follow:—

$$\left. \begin{array}{l} \text{Ampere-turns required to drive} \\ N \text{ lines through iron of armature} \end{array} \right\} = N \times \frac{l_1}{A_1 \mu_1} \div \frac{4 \pi}{10};$$

$$\left. \begin{array}{l} \text{Ampere-turns required to drive} \\ N \text{ lines through the two gap spaces} \end{array} \right\} = N \times \frac{2 l_2}{A_2} \div \frac{4 \pi}{10};$$

$$\left. \begin{array}{l} \text{Ampere-turns required to drive} \\ v N \text{ lines through the iron of field-} \\ \text{magnet} \end{array} \right\} = v N \times \frac{l_3}{A_3 \mu_3} \div \frac{4 \pi}{10};$$

and, adding up:

$$\text{Total ampere-turns required} = \frac{10}{4 \pi} N \left\{ \frac{l_1}{A_1 \mu_1} + \frac{2 l_2}{A_2} + \frac{v l_3}{A_3 \mu_3} \right\}.$$

(b) *If the dimensions are given in inches, the rule is:—*

Ampere-turns = magnetic flux multiplied by magnetic
reluctance;

or, in detail:

$$\left. \begin{array}{l} \text{Ampere-turns required to drive} \\ \text{N lines through iron of arma-} \\ \text{ture} \end{array} \right\} = \dot{\mathbf{N}} \times \frac{l'_1}{A''_1 \mu_1} \times 0.3132;$$

$$\left. \begin{array}{l} \text{Ampere-turns required to drive} \\ \text{N lines through two gap} \\ \text{spaces} \end{array} \right\} = \mathbf{N} \times \frac{2l''_2}{A''_2} \times 0.3132;$$

$$\left. \begin{array}{l} \text{Ampere-turns required to drive} \\ v \text{ N lines through iron of field-} \\ \text{magnets} \end{array} \right\} = v \mathbf{N} \times \frac{l'_3}{A''_3 \mu_3} \times 0.3132;$$

and, adding up:

$$\left. \begin{array}{l} \text{Total ampere-turns} \\ \text{required} \end{array} \right\} = 0.3132 \mathbf{N} \left\{ \frac{l'_1}{A''_1 \mu_1} + \frac{2l''_2}{A''_2} + \frac{v l'_3}{A''_3 \mu_3} \right\}.$$

[Example: in a certain Lahmeyer dynamo, with cast iron magnets, the following were the data: $\mathbf{N} = 2,328,000$; $v = 1.11$; $l'_1 = 6\frac{3}{4}$; $l''_2 = \frac{1}{2}$; $l'_3 = 40$; $A''_1 = 34.8$ sq. in.; $A''_2 = 69.5$; $A''_3 = 86.5$: calculate the required ampere-turns.]

In some forms of dynamo the magnetic reluctances of pole-pieces and yokes must be separately calculated; and allowance must in some cases be made for leakages at different parts of the circuit. Hence a more careful formula would be:—

$$S C = 0.3132 \mathbf{N} \left\{ \frac{l'_1}{A_1 \mu_1} + \frac{2l''_2}{A_2} + \frac{v_3 l'_3}{A_3 \mu_3} + \frac{v_4 l'_4}{A_4 \mu_4} + \frac{v_5 l'_5}{A_5 \mu_5} \right\}$$

It is expedient that the calculation of the ampere-turns should be made *twice*; that is once (using the value of $\mathbf{N}$ that corresponds to the case of no lost volts) to find the value of the ampere-turns of winding to be put on the shunt, when there is no current through the lamps; and once (using the higher value of $\mathbf{N}$ that corresponds to the maximum E) to find the increased ampere-turns that are required when the full current is being taken from the armature. These will have to be provided for (in compound-wound machines) by a series coil to compensate for demagnetizing effect of armature, as well as for the lost volts.

- § 20. *To Estimate the Additional Ampere-turns Required to Compensate for the Demagnetizing Action of the Armature Current when the Brushes have a Forward Lead.*

Count the number of conductors on periphery, between the diameter of symmetry and the actual diameter of commutation, and multiply by C_a the amperes flowing through armature. The product so found will have to be increased by a certain amount on account of the drop in magnetic potential which takes place in the field core owing to the increased magnetic leakage and decreased permeability of the core. This cannot be estimated without going over the magnetic calculations in the manner shown on p. 365: in practice the product must be increased from $1\frac{1}{2}$ to 2 times. For ring machines the product must be doubled. The number so determined must then be added to the number of ampere-turns previously calculated.

EXAMPLES OF CALCULATIONS APPLIED TO CONTINUOUS-CURRENT DYNAMOS.

As remarked at the opening of the present chapter, it is advantageous to go over the calculation of some existing machines. Two complete examples are given here, one relating to an Edison-Hopkinson dynamo (see pp. 148, 152, and 403); the second to a Kapp dynamo, Plates I. and II. The magnetic-circuit calculations for the first have been calculated out in C.G.S. units; those in the second in inch units, so as to show both modes of calculation. As a third example, an exercise for calculation is given.

EXAMPLE I.—AN EDISON-HOPKINSON DYNAMO.

Description adapted from paper by J. and E. Hopkinson, in *Phil. Trans.*, 1886. (See Fig. 287, p. 422.)

Shunt-Wound Dynamo, with Drum Armature: 33 kilowatts
Output: 320 Amperes, at 105 volts, at 750 revolutions per minute.

Armature: Built up of about 1000 iron core plates stamped out of soft sheet iron separated by sheets of paper, and held between two end-plates, one of which is secured by a washer shrunk on

The magnetizing coils are wound directly on the limbs, and consist of 11 layers on each limb of copper wire 0.100 inch, or 2.413 mm. diameter (No. 13 B. W. G.), having, therefore, cross section of 0.0071 sq. in. or 4.573 sq. mm., making 3260 convolutions in all; total length being approximately 15,000 feet, or 4570 metres. Resistance at 13.5° C. is 16.93 ohms.

Data for Calculating Reluctances in Magnetic Circuit.

1.—*Armature Core.*

l_1 taken as $5\frac{1}{2}$ inch or 13 cm.

A_1 taken as 125 sq. in. or 810 sq. cm.

2.—*Gap Space.*

l_2 is $1\frac{1}{2}$ inch (= 0.59 inch), or 1.5 cm.

A_2 taken as 248 sq. in. or 1600 sq. cm. This allows $29\frac{1}{2}$ sq. inch, or 190 sq. cm. for fringing. The actual area of the polar face is $234\frac{1}{2}$ sq. in., or 1513 sq. cm.; and the corresponding area of 129° of surface of armature core is $218\frac{1}{2}$ sq. in., or 1410 sq. cm. Allow, for fringing, a margin all round equal to four-fifths of gap-space.

3.—*Magnet Limbs.*

l_3 is in total 36 inch, or 91.4 cm.

A_3 is taken at 152 sq. inch, or 980 sq. cm.

4.—*Yoke.*

l_4 is taken at $19\frac{1}{2}$ inch, 49 cm., estimated along quadrants.

A_4 is $173\frac{1}{2}$ sq. inch, or 1120 sq. cm.

5.—*Pole Pieces.*

l_5 is $4\frac{1}{2}$ inch, or 11 cm., estimated along curve.

A_5 is taken as $190\frac{1}{2}$ sq. inch, or 1230 sq. cm.; being mean area between section of limb and area of polar face.

Coefficient of leakage v was taken by Hopkinson as 1.32, but was probably nearer 1.4.

CALCULATIONS ABOUT THIS DYNAMO.

$C = 320$; $e = 105$; $n = \frac{750}{60} = 12.5$; $r_a = 0.01$; $r_s = 16.93$, whence $C_s = e \div r_s = 6.21$; $C_a = C + C_s = 326$; lost volts $= r_a \times C_a = 0.01 \times 326 = 3.26$; hence $E = e + r_a C_a = 108.26$ at full load. $Z = 80$.

$$N = \frac{E \times 100,000,000}{n Z} = \frac{108.26 \times 10}{12.5 \times 80} = 10,826,000.$$

$$\text{Useful watts} = e \times C_a = 105 \times 320 = 33,600.$$

Total watts = $E \times I_a$	= $208 \cdot 36 \times 336 = 35,293$.
Electrical efficiency,	= useful watts $\div$ total watts.
	= $10,922$ or $95 \cdot 2$ per cent.
Watts lost in armature	= $I_a^2 R_a$ = amperes.
	= $3 \cdot 36 \times 336 = 1062 \cdot 76$.
Watts lost in magnets	= $I_m^2 R_m$ = volts.
	= $1 \times 116 = 630$.
Watts lost by hysteresis	= $12 \cdot 5$ reversals per sec. in $0 \cdot 7$ cubic
	feet at $13,360$ for B , see p. 140.
	= 211 .

To find ampere-turns requisite to magnetize. By § 19 above;
 $S C = \frac{10}{4} \times 20,826,000 \div$ the total magnetic reluctance.

This must be determined from the B data of the magnetic circuit in separate parts as in p. 141. First find values of B in separate parts according to leakage and cross-section, and from these values find corresponding values of λ by Table I., p. 126, or from Fig. 85.

1. Armature	$B_1 = 13,360; \lambda_1 = 1000$
3. Magnet limbs	$B_3 = 14,250; \lambda_3 = 796$
4. Yoke	$B_4 = 13,330; \lambda_4 = 895$
5. Pole-pieces	$B_5 = 11,450; \lambda_5 = 1566$

Inserting these values and those of the leakage coefficients, the magnetic reluctances come out:—

1. Armature	0·00001605
2. Gap-spaces	0·00187500
3. Magnet limbs	0·00015467
4. Yoke	0·00006845
5. Pole-pieces	0·00000151

Total magnetic reluctance .. 0·00211568

Whence

$$S C = \frac{10}{4} \times 10,826,000 \times 0.00211568$$

$$= 15226.$$

To this must be added the ampere-turns needed to compensate for demagnetizing action of armature. The number of armature con-

ductors between pole-tips is 11; but as the diameter of commutation is not quite at the pole-tips we take 9 as the demagnetizing belt. Multiplying this by half the armature current (163 amperes), and by the leakage coefficient (1.32) we get 1936 as the compensating number, making total requisite ampere-turns 20,162. Dividing this by the number of amperes of current allowed in the shunt-coil (6.21) gives 3214 as the requisite number of coils S on the field-magnet. The actual number wound on was 3260, which allows a margin for regulating.

EXAMPLE II.—THE KAPP DYNAMO.

Compound-Wound Dynamo with Drum Armature (Over Type)
—Output 21 kilowatts; 200 amperes at 105 volts. Speed, 780 revolutions per minute. (Shown in Fig. 259 and Plates I., II. and III.) The *Armature*, which is described on p. 307, has the following dimensions:—

Core-disks, external diam.	..	$11\frac{1}{8}$ in., 28.2 centim.
“ internal diam.	..	$6\frac{5}{8}$ “ 19 “
Shaft diam.	.. . . .	$2\frac{1}{2}$ “ 7.1 “
Radial depth of iron	.. . . .	$2\frac{3}{8}$ “ 6 “
Gross length of core	.. . . .	16 “ 40.6 “
Total thickness paper insulation.	..	$2\frac{1}{8}$ “ 7.3 “
Nett thickness of iron in core	..	$13\frac{1}{4}$ “ 33.3 “
Nett cross section of iron, A_1	..	62.5 sq. in., 403 sq. cm.
Effective length, l_1	.. . . .	5.5 in., 13.9 cm.

Particulars of conductors, etc.:

Number of conductors	.. . .	120
Breadth.	.. . . .	0.11 in., 0.279 centim.
Radial depth	.. . . .	0.208 in., 0.528 “
Section of conductor	.. . . .	0.046 sq. in., 0.297 sq. cm.
Total diam. of armature	.. . .	$11\frac{1}{8}$ in., 29.6 centim.
Diam. of bore of poles	.. . .	$11\frac{1}{8}$ in., 30.3 centim.
Resistance of armature (hot)	..	0.025 ohm.

The commutator has 60 segments insulated with mica.

The conductors are joined at the end of the armature by 120 semicircular connectors, each of which is 1.625 inch, or 4.1 cm.

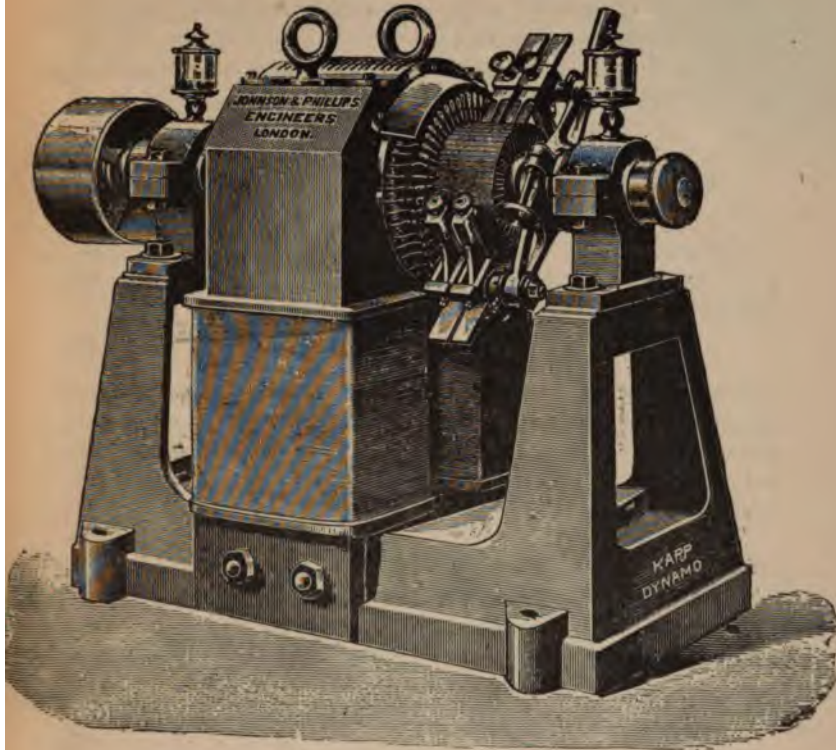


FIG. 259.—THE KAPP DYNAMO.

CALCULATIONS ON OPEN CIRCUIT.

The calculations in this case will be made throughout in inch measure.

ARMATURE.—The first operation is to find the number of lines of force that must be passing through the armature in order that 105 volts shall be generated in it.

Taking the formula

$$N = \frac{60 \times 10^8 \times E}{Z + \text{revs. per min.}}$$

and substituting the values given above

$$\begin{aligned} N &= \frac{60 \times 10^8 \times 105}{120 \times 780} \\ &= 6,732,000 \quad \dots \dots \dots (\alpha) \end{aligned}$$

This gives the number of lines passing through the armature.—Dividing the above figure by the sectional area of the armature, we obtain the number of lines passing through each square inch of the armature ; this is denoted by the letter B_1 .

$$\begin{aligned} B_1 &= \frac{6,732,000}{62.5} \\ &= 107,600 \quad \dots \dots \dots (b) \end{aligned}$$

This gives the flux-density in the armature.—On reference to the curve for wrought iron connecting μ_1 and B_1 (p. 125) we find that at this flux-density

$$\mu_1 = 210. \quad \dots \dots \dots (c)$$

FIELD-MAGNETS.—*To find the number of lines passing through the field-magnets* it is only necessary to multiply the value (a) by the coefficient of leakage, which by experiment has been found to be about 1.3 in this class of machine.

$$\begin{aligned} N_2 &= 6,732,000 \times 1.3 \\ &= 8,750,000 \quad \dots \dots \dots (d) \end{aligned}$$

This value divided by the sectional areas of magnet-limbs and yoke respectively gives the flux-densities through them. Thus

$$\begin{aligned} B_2 &= \frac{8,750,000}{105} \\ &= 83,330 \quad \dots \dots \dots (e) \end{aligned}$$

This is the flux-density in the magnet-limbs, and on reference to Hopkinson's curve this corresponds to a

$$\mu_2 = 1230 \quad \dots \dots \dots (f)$$

And in the yoke whose cross-section is 180 sq. in.

$$\begin{aligned} B_3 &= \frac{8,750,000}{180} \\ &= 48,610 \quad \dots \dots \dots (g) \end{aligned}$$

This is the flux-density in the yoke, and on reference to Hopkinson's curve for cast-iron, this corresponds to a permeability

$$\mu_3 = 125 \quad \dots \dots \dots (h)$$

It will be noticed in these calculations that the pole-pieces are added in the magnet-limbs, which may be done without appreciable error in this type of machine.

MAGNETIC RELUCTANCE.—The next step is to find the ampere-turns per line needed for each part of the magnetic circuit, and this is done by substituting the values for the length, section and μ in the reluctance formula given on p. 350, viz. :—

$$\frac{l}{\mu A} \times 0.3132.$$

So we get for the

Armature	$= \frac{5.5 \times 0.3132}{210 \times 62.5}$	
	$= 0.0001312$	(i)
Magnet limbs	$= \frac{2 \times 23 \times 0.3132}{1230 \times 105}$	
	$= 0.0001115$	(j)
Yoke	$= \frac{7 \times 0.3132}{125 \times 180}$	
	$= 0.00009743$	(k)

Air-gap.—The length of each air-gap is $\frac{7}{16}$ ", but the area of the polar face must be found by calculation from the diameter of the magnet bore, the angle subtended by the polar face, and the breadth of the magnet, thus:—

$$\begin{aligned} \text{Area} &= 15 \times \pi d \times \frac{135}{360} \\ &= \frac{15 \times 3.1416 \times 11\frac{1}{8} \times 135}{360} \\ &= 211 \text{ square inches.} \end{aligned}$$

Correction for Fringing.—To correct for fringing the following is a practical rule:—Add to the actual area of the polar face an area whose length is equal to the periphery of the polar face, and whose breadth is equal to the length of the air-gap multiplied by 0.8.

The periphery in the above case is $15'' + 14'' + 15'' + 14''$ and air-gap is $\frac{7}{16}$ ". The correction for fringing is, therefore,

$$(15 + 14 + 15 + 14) \times \frac{7}{16} \times 0.8 = 20.3 \text{ square inches} \quad (l)$$

The effective area of the polar face is, therefore,

$$211 + 20.3 = 231.3 \text{ square inches.}$$

$$\therefore \text{reluctance of air-gaps} = \frac{2 \times \frac{7}{16} \times 0.3132}{231.3}$$

$$= 0.001185 \dots \dots \dots (m)$$

CALCULATED AMPERE-TURNS.

The next and final step is to find the number of ampere-turns, or magnetomotive-force, required to drive the given number of lines through the different portions of the magnetic circuit. This is found by multiplying the number of lines in any part by the magnetic reluctance of that part, thus:—

Armature (ampere-turns)	$SC = 6,732,000 \times 0.0001312$	
	$= 883.5$	(n)
Air-gaps	$SC = 6,732,000 \times 0.001185$	
	$= 7,975$	(o)
Magnet limbs	$SC = 8,750,000 \times 0.0001115$	
	$= 976.1$	(p)
Yoke	$SC = 8,750,000 \times 0.00009743$	
	$= 852.5$	(q)

SUMMARY.

Ampere-turns required for armature	=	883.5
“ “ air-gaps	=	7,975.0
“ “ magnet limbs	=	976.1
“ “ yoke	=	852.5
Total		10,687.1

Our calculations, then, lead us to the conclusion that there must be 10687.1 ampere-turns wound on the shunt circuit, in order to drive sufficient lines through the armature to enable the dynamo to give 105 volts on open circuit at a speed of 780 revolutions per minute. Let us see how this result agrees with what actually exists on the machine

ACTUAL AMPERE-TURNS.

The resistance of the shunt circuit is 30.1 ohms, and the pressure at its terminals of 105 volts. The current flowing through the shunt is, therefore,

$$C_s = \frac{105}{30.1} = 3.488 \text{ amperes} \quad (r)$$

and as there are 3058 turns of wire, the number of ampere-turns on the field-magnet is

$$S C = 3058 \times 3.488 = 10,670, \quad (s)$$

which agrees almost exactly with the figure obtained by calculation.

CALCULATIONS AT FULL LOAD.

Since there is now a current of rather over 200 amperes flowing through the armature and series coils, there is necessarily a fall of pressure there, and as the terminal pressure must remain the same as before, the dynamo is called upon to generate a pressure equal to the sum of these two. The fall of pressure in the armature and series coils is obtained by multiplying their resistance by the current.

$$\text{Thus } 200 (0.025 + 0.0079) = 6.58 \text{ volts.}$$

Therefore, the total E.M.F. required to be generated by the dynamo is

$$\text{E.M.F.} = 105 + 6.58 = 111.58 \text{ volts.}$$

A similar set of calculations to the previous ones must now be made, assuming the new value of the E.M.F. thus

$$\begin{aligned} \text{Lines through armature} \quad N' &= \frac{60 \times 10^8 \times 111.58}{780 \times 120} \\ &= 7,153,000 \quad . . . (a) \end{aligned}$$

$$\begin{aligned} \text{Flux-density in armature} \quad B'_1 &= \frac{7,153,000}{62.5} \\ &= 114,500 \quad . . . (b') \end{aligned}$$

$$\text{Corresponding to} \quad \mu'_1 = 100 \quad . . . (c')$$

$$\begin{aligned} \text{Lines through field-magnets} \quad N'_2 &= 7,153,000 \times 1.3 \\ &= 9,298,000 \quad . . . (d') \end{aligned}$$

$$\begin{aligned} \text{Flux-density in limbs} \quad B'_2 &= \frac{9,298,000}{105} \\ &= 88,550 \quad . . . (e') \end{aligned}$$

$$\text{Corresponding to} \quad \mu'_2 = 950 \quad . . . (f')$$

$$\begin{aligned} \text{Flux-density in yoke} \quad B'_3 &= \frac{9,298,000}{180} \\ &= 51,650 \quad . . . (g') \end{aligned}$$

$$\begin{aligned} \text{Corresponding to} \quad \mu'_3 &= 95 \quad . . . (h') \end{aligned}$$

MAGNETIC RELUCTANCES.

Armature	$= \frac{5.5 \times 0.3132}{100 \times 62.5}$	
	$= 0.0002756$	(i)
Magnet-limbs	$= \frac{2 \times 23 \times 0.3132}{950 \times 105}$	
	$= 0.0001444$	(j)
Yoke	$= \frac{7 \times 0.3132}{95 \times 180}$	
	$= 0.0001218$	(k)
Air-gaps	$= 0.001185$ (as before).	

CALCULATED AMPERE-TURNS.

Armature	$S C = 0.0002756 \times 7,153,000$	
	$= 1,972$	(n)
Air-gaps	$S C = 0.0011850 \times 7,153,000$	
	$= 8,474$	(o)
Magnet-limbs	$S C = 0.0001444 \times 9,298,000$	
	$= 1,343$	(p)
Yoke	$S C = 0.0001218 \times 9,298,000$	
	$= 1,132$	(q)

SUMMARY.

Ampere-turns required for armature	$= 1,972$
“ “ air-gaps	$= 8,474$
“ “ magnet-limbs	$= 1,343$
“ “ yoke	$= 1,132$
Total	12,921

It is thus seen that 12,921 ampere-turns must be used instead of 10,687, in order to compensate for the lost volts in the armature. But even this increased number will not be sufficient to bring about the required result, owing to the demagnetizing effect which the armature exercises. It is found that there are eight conductors in the angle of lead at full load. This number multiplied by the current gives us 1600 demagnetizing ampere-turns. Now we see from (n') and (o') above that the magnetic potential between the pole pieces required to drive the flux through the armature and air-gaps is that of 10,446 ampere-turns. To this must be added a potential equivalent to 1600 ampere-turns to overcome the demagnetizing effect of the armature. Now if the difference of

magnetic potential between the poles is raised in this way the magnetic leakage will be raised proportionately. The coefficient of leakage will therefore be nearer 1.4 than 1.3. This means that the flux through the limbs and yoke is increased to about 10,000,000 lines. Taking the flux density in the limbs at 95,000 and in the yoke at 55,000, we have μ'_2 and μ'_3 reduced to about 750 and 75 respectively, and the ampere-turns required for these parts increased to 800 and 1500 respectively. Adding together the ampere-turns required to overcome the demagnetizing effect, and the reluctances of the air-gaps, armature, limbs and yoke, we get a total of 15,300.

Having now completed the calculations, let us set them down in a model schedule for use in future designs.

		B _h	μ	Reluctance.	Ampere-turns required.
Open Circuit.	Armature ..	107,600	210	0.0001312	883.5
	Air-gaps.. ..	29,000	1	0.001185	7,975
	Magnet-limbs	83,330	1,230	0.0001115	976
	Yoke	48,610	125	0.0000974	852.5
	Total				10,687
Full Load.	Armature ..	114,500	100	0.0002756	1,972
	Air-gaps.. ..	31,000	1	0.001185	8,474
	Magnet-limbs	95,000	750	0.000180	1,800
	Yoke	55,000	75	0.000150	1,500
					13,746
Required to counteract demagnetization =					1,600
Total					15,346

ACTUAL AMPERE-TURNS.

Let us compare this with what actually exists on the dynamo, and we find

Ampere-turns of shunt-winding = 10,670 (as before).
 " series winding (23×200) = 4,600
 Total 15,270

In practice the number of series ampere-turns cannot be foretold with the accuracy shown by the above figures. The usual course is to wind upon the dynamo the approximate number of series turns, and by running the machine find by experiment exactly how many ampere-turns are required to keep the volts at the desired amount at full load, and then the series winding is adjusted accordingly.

Example III. (already partly considered on pp. 340 to 344).

Design of a single-field compound-wound dynamo, with drum armature. Output 200 amperes at 55 volts at 1140 revolutions per minute. It is required to find the appropriate field-magnet.

Armature.—Built up of core-disks, separated by varnished manilla paper fixed by end-clamping upon a three-webbed sleeve of gun-metal. Shaft of Siemens steel. Commutator 36 parts. Conductors 72 all round periphery, in one layer. Hence at full load N must be about 4,170,000 lines; and at 90,000 lines to square inch this needs a nett cross-section of 45 square inches in core. Core disks, $7\frac{1}{2}$ inches exterior diameter, $4\frac{1}{2}$ inches interior diameter, in sufficient numbers to make up total nett length of 15 inches. Core disks are 28 mils (i. e. No. 22 S.W.G.) thick, so that about 536 of them are needed. Conductor, a stranded wire of 7 No. 13, overspun together with double cotton covering, and already lightly varnished with Scott's rubber varnish. Resistance of armature from brush to brush 0.007 ohm; length of armature winding, approximately 52 yards.

Field-magnets.—Horizontal limbs of best cast iron carefully annealed, lower one forming part of bed-plate casting. Section widening from lips so as to have section 194 square inches, and at parts furthest from armature $16\frac{1}{2}$ inches wide by 11 inches deep, being bored out to receive the ends of the wrought-iron magnet core, which is a round forging, $10\frac{1}{2}$ inches diameter, turned down at its ends to 10 inches diameter, where it is inserted into the horizontal pole-pieces. The finished machine generally resembles Fig. 102, p. 163, but is more massive in the field-magnets.

To find the proper length for this core, first make an approximate estimate of the needed number of ampere-turns, and thence calculate the quantity of windings and the proper length of core to receive the wire. Then design the magnetic circuit to be as compact as possible; and having so settled the sizes of the parts, calculate more exactly, as in the preceding example, the requisite number of ampere-turns to be provided on open circuit and at full load.

An example of a very detailed calculation of a dynamo is given by Wiener in the *Electrical World*, xxv. 662, June 8, 1895.

Experienced designers, accustomed to work at particular types

of machine, and with particular brands of iron, are able to simplify down their methods of calculation. They will, for example, settle by experience to design their machines to work at certain definite flux-densities in cores of armature and of magnets—hence at known permeabilities. They can then fix the number of ampere-turns needed per inch of length in each part of the magnetic circuit; and with the drawings before them can in a few moments determine the total ampere-turns needed for excitation.

USEFUL POINTS IN DESIGNING.

Peripheral Speeds.—The usual peripheral speeds appear to be from 2700 to 3000 feet per minute (*i. e.* 12 to 15 meters per second) for drums and cylindrical rings. For drum armatures destined for an output of K kilowatts, the suitable speed may be calculated by the formula $s = 3000 K \div K + 1$. For large low-speed ring machines we may take $s = 2700 K \div K + 5$. Esson maintains that 6000 feet per second can be safely attained in large machines. For discoidal rings and disk armatures, 3000 to 5000 feet per minute is usual. Ferranti's 15-foot armatures (Fig. 418) have peripheral speed of 5400 feet per second. Those alternators in which the field-magnet revolves may have higher peripheral speeds without risk of flying to pieces, some going over 7000 feet per minute. In the Niagara alternators the speed is 7854 feet per minute.

Core-disks—These are usually from 25 to 50 mils in thickness, in continuous-current dynamos and motors. For alternate-current machines some makers use thinner stampings.

For rings, the ratio used in practice between the external and internal diameters is from 10 to 8 in small rings to 10 to 7 in large rings. In Brown's 4-pole rings (Fig. 276) the ratio is 10 to 7; in his 8-pole rings (Fig. 279) about 10 to 8. In Siemens' machines with internal magnets (Plate VIII.) the ratio is about 10 to 9. In machines with cast-iron magnets, the rings are usually made with a less radial depth of iron than in machines of wrought iron.

For bipolar drums, the usual ratio of external and internal diameters is 10 to 3. In Kapp's 2-pole machine (Plate I.) the ratio is 7 to 4. For multipolar drums greater internal

space is usual. In Brown's 6-pole drum (Fig. 240) the ratio is 5 to 3.

Proper Flux-density.—The limiting values to which it is found expedient in practice to push the flux-density have been several times alluded to. The values of **B** are here tabulated for convenience. As a rule the higher flux-densities are admissible in the larger sizes only.¹ It seems to be recognized that the flux-density in the gap-space may be higher if the poles are of wrought iron or mild steel than if they are of cast iron.

Flux-density B — Lines per sq. cm.				
Species of Dynamo.	In Armature.	In Gap-Space.	In Field-Magnet.	
			Wrought Iron.	Cast Iron.
<i>Constant Potential Machines</i>				
2-Pole Drum	10,000 to 15,000	2,500 to 6,500	12,000 to 17,000	6,000 to 8,000
2-Pole Ring (long) ..	12,000 to 16,000	2,500 to 5,000	12,000 to 17,000	6,000 to 8,000
Multipolar Rings ..	10,000 to 15,000	3,000 to 8,500	12,000 to 17,000	6,000 to 8,000
<i>Arc-Light Machines</i>				
	17,000 to 20,000	3,000 to 7,000	17,000 to 20,000	6,000 to 10,000
<i>Accumulator-charging Machines.</i>				
	10,000 to 13,000	4,000 to 6,000	10,000 to 15,000	5,000 to 7,000
<i>Alternators</i>				
Multipolar Ring ..	6,000 to 6,500	2,500 to 4,000	12,000 to 17,000	6,000 to 8,000
„ Drum ..	6,000 to 7,000	2,500 to 5,000	12,000 to 17,000	6,000 to 8,000
Coreless Disk	5,000	5,000	12,000	6,000

Specific Utilization of Copper.—Those machines in which the material is used to the greatest advantage will have the largest output in proportion to weight. Considering the

¹ See statistics by Wiener in *Electrical World*. xxiii. 713, 1894, where, however, teeth on cores are erroneously regarded as causing leakage through the armature.

copper in the armature only, the number of watts of output per lb. of copper will obviously be greater the denser the field and the higher the linear speed. Taking an average field of about 3000 lines per sq. cm., the watts per lb. of copper vary from below 100 in multipolar ring slow-speed machines to 500 or 600 in bipolar drum high-speed machines.

The length of wire to produce a given voltage at a given speed is a measure (inversely) of the density of magnetic field. The following are examples of 2-pole drum-wound dynamos:—Edison-Hopkinson, at 750 revolutions per minute, takes 19 inches per volt; Kapp at 780 revolutions per minute, 35 inches per volt; Thomson-Houston arc-lighter, at 900 revolutions per minute, 148 inches per volt. With a peripheral speed of 3000 ft. per minute, in a field where the flux density is 6000, each inch of conductor generates about $\frac{1}{4}$ volt.

Size of Wire for Winding Armatures.—This will be further discussed under heading of permissible heating. Modern practice allows from 2000 to 3000 amperes persquare inch, in conductors of ring-armatures, and even up to 4000 amperes per square inch in those with single-layer surface winding; but in the magnet coils only about 2000 amperes per square inch. Esson¹ has given a useful table of usual sizes of wire used in winding armatures to run at usual speeds, together with the number of layers of each that may be used for these currents without overheating.

Heating of Magnetic Coils.—All field-magnet coils are liable to heat, because even the purest copper offers resistance. If it be assumed that the thickness of the insulation is proportional to the thickness of the wire on which it is wound, it follows that the weight of copper in a coil filling a bobbin of given dimensions will be the same, whether a thick wire or a thin one be employed. Further, for a given volume to be filled with coils, the number of ohms of resistance of the coil will vary *directly as the square of the number of turns* in the coil. For if a coil wound with 100 turns of a given gauge be rewound with 200 turns of wire having half the sectional area, the resistance of this new winding will obviously be four times as great as that of the original wind-

¹ *Elec. Review*, xxvii. 546 (1891).

ing. Also, by a similar argument, it follows that the resistance of a coil of given volume will vary *inversely as the square of the sectional area* of the wire used. And as this area is proportional to the square of the diameter of the wire, it follows that the resistance is *inversely proportional to the fourth power of the diameter* of the wire used. (See also Appendix A.)

The amount of heat developed per second in a coil is the product of the resistance into the square of the strength of the current. To avoid waste, therefore, no unnecessary resistance should be introduced into any main-circuit coil. It is easy to show that with a coil of *given volume*, the heat-waste is the same for the same magnetizing power, no matter whether the coil consists of few windings of thick wire or many windings of thin wire. The heat per second is $C^2 r$; and the magnetizing power is SC ; C being the current, r the resistance, and S the number of turns. But r varies as the square of S , if the volume occupied by the coils is constant. For suppose we double the number of coils, and halve the cross-sectional area of the wire, each foot of the thinner wire will offer twice as much resistance as before; and there are twice as many feet of wire. The resistance is quadrupled therefore. The heat is then proportional to $C^2 S^2$: and therefore the heat is proportional to the square of the magnetizing power. If, therefore, we apply the same magnetizing power by means of the coil, the heat-waste is the same, however the coil is wound. To magnetize the field-magnets of a dynamo to the same degree of intensity requires the same expenditure of electric energy, whether they are series wound or shunt wound, provided the volume is the same.

A simple way of looking at this matter is to regard the whole winding as consisting of one turn, there being a current, equal to the total ampere-turns, going only once round. Then this current divided by the total cross section of copper gives the current-density. We then see that for equal-sized bobbins (containing the same amount of copper) the magnetizing effect is simply proportional to the current density. Further, the power wasted per lb. of copper is proportional to the square of

the current-density. The following table gives the waste in watts for different current-densities in both inch and centimetre measure. The temperature of the coil is taken at 30° C., at which temperature the resistance of an inch cube of copper may be taken at 0.7×10^{-6} ohm.

LOSS OF POWER IN COPPER CONDUCTORS AT DIFFERENT CURRENT-DENSITIES.

Current-density.		Watts converted into Heat.		
Amperes per sq. in.	Amperes per sq. cm.	Per cubic in. of Copper.	Per cubic cm. of Copper.	Per lb. of Copper.
1000	155	0.7	0.042	2.17
1500	232	1.57	0.096	4.88
2000	310	2.8	0.171	8.71
2500	387	4.37	0.266	13.59
3000	465	6.3	0.384	19.59
3500	542	8.5	0.510	26.43
4000	620	11.2	0.683	34.83

If the *volume* of the coil (and the weight of copper in it) may be increased, then the heat-waste may be proportionally lessened. For example, suppose a shunt coil of resistance r has S turns; if we wind on another S turns in addition, the magnetizing power will remain nearly the same, though the current will be cut down to one-half owing to the doubling of the resistance; and the heat-loss will be halved, for $2r \times (\frac{1}{2}C)^2$ will be $\frac{1}{2} C^2 r$.

It is assumed in the foregoing argument that we get double the number of turns on if we halve the sectional area of the copper wire. This is not quite true, because the thickness of the insulating covering bears a greater ratio to the diameter of the wire for wires of small gauge than for wires of large gauge. In designing dynamos, moreover, one ought to be guided by the question of economy, not by the accident of there being only a certain volume left for winding. If there is insufficient space round the cores to wind on the amount of

wire that economy dictates, new cores should be prepared having a sufficient length to receive the wire which is economically appropriate.

In order to calculate the diameter of the wire to be used in a shunt coil, we must first estimate the mean length of one turn. This can be done with considerable accuracy when the circumference of the iron limb and the approximate depth of winding are known. The diameter of the wire d must be such that the resistance ρ of one turn divided into the volts at the terminals of the shunt will give the total ampere-turns required, or in symbols

$$SC = \frac{e}{\rho}.$$

If the bobbins are to be circular and of mean diameter δ we know that

$$\rho = \frac{\delta \times \pi}{d^2 \times \frac{1}{4} \pi} \times 1.9 \times 10^{-6}.$$

Hence the diameter of the wire in centimetres will be

$$d = \sqrt{\frac{SC \times \delta \times 4 \times 1.9}{e \times 10^6}}.$$

Example.—What thickness of copper wire must be used to wind a pair of shunt coils in order to obtain an aggregate of 18,930 ampere-turns, the winding on each cylindrical bobbin having a mean diameter of 17 centimetres, if the pressure at the terminals of the magnet is intended to be 100 volts (the two coils being in series with each other). *Answer:* 0.156 cm.

We have taken the resistance of a centimetre cube of copper to be 1.9×10^{-6} ohm. at 50° C. The figure will of course vary with the temperature of the coil. If the measurements are expressed in inches, we have

$$d_{\text{in}} = \sqrt{\frac{SC \times \delta_{\text{in}} \times 4 \times 0.75}{e \times 10^6}}.$$

If no special limit of temperature-rise is prescribed, then the dominant consideration that governs the length of wire

used in winding is the amount of energy that may be wasted in magnetizing. If a temperature-limit is prescribed, then there must be provided a cooling-surface proportional to the energy that is wasted in the magnetizing coil. Experience shows that if the heating is not to exceed 20° to 25° (Cent.) above atmospheric temperature, at least $2\frac{1}{2}$ square inches of external surface of coil must be allowed for each watt wasted by the coil's resistance. Or, conversely, if a bobbin has room for a coil of only a certain amount of surface, a winding must be chosen such that it will waste only one watt for each $2\frac{1}{2}$ square inches of surface.

For shunt coils the length, and therefore the volume, is dictated solely by reasons of economy. It is usual to allow 25 to 40 yards per volt.

Permissible Heating and Surface of Emission.—In order that any coil may not overheat it must have sufficient surface relatively to the amount of heat developed in it by the current. In the Brush arc dynamo, 2 sq. inches of surface per watt lost are allowed in the field-magnets, and 0.9 sq. inches in the armatures; in the Thomson-Houston armature, 1.66 sq. inches. The relation between the heat developed, the surface of emission, and the resulting rise of temperature has been investigated by Forbes, Esson and others. Esson finds that from surfaces consisting of wire double cotton-covered and varnished heat will be emitted at the rate of $\frac{1}{365}$ of a watt¹ from 1 square centimetre if warmed 1° C. above the surrounding atmosphere. Within the range of ordinary heating it may be assumed that the rate of emission is proportional to the excess of temperature over the surrounding air.

¹ The *watt* is the unit of rate of expenditure of energy, and is equal to ten million ergs per second, or to $\frac{1}{746}$ of a horse-power. A current of one ampere flowing through a resistance of one ohm, spends energy in heating at the rate of one watt. One watt is equivalent to 0.24 calories per second, of heat. That is to say, the heat developed in one second, by expenditure of energy at the rate of one watt, would suffice to warm one gramme of water through 0.24 (Centigrade) degrees. As 252 calories are equal to one British lb. (Fahrenheit) unit of heat, it follows that heat emitted at the rate of one watt would suffice to warm 3.4 pounds of water one degree Fahrenheit in one hour; or one British unit of heat equals 1050 watt-seconds.

Esson's rule, which appears to agree with the experience of various different makers, may then be stated

$$\theta^{\circ} \text{C} = 355 \frac{w}{s};$$

where θ stands for the rise of temperature, w is the watts expended in heat in the coil, and s its surface in sq. cms. Or, if Fahrenheit degrees and sq. inches are used, the rule becomes

$$\theta^{\circ} \text{F} = 100 \frac{w}{s}.$$

In using such rules, and calculating the watts developed in the coil (by multiplying the resistance by the square of the current), it must be remembered that the wire when warm has a higher resistance than when cold. A useful rule to take this into account is:—

To find resistance (hot) when resistance (cold) is known; add to the known number of ohms 1 per cent. for every $2\frac{1}{2}$ Centigrade degrees, or for every $4\frac{1}{2}$ Fahrenheit degrees.

To find maximum permissible current, if the rise of temperature θ is prescribed as a limit.

$$\text{Max. permissible current} = \sqrt{\frac{\theta^{\circ} \text{C} \times \text{sq. cm.}}{355 \times \text{resistance (hot)}}};$$

or

$$\text{Max. permissible current} = \sqrt{\frac{\theta^{\circ} \text{F} \times \text{sq. inches}}{100 \times \text{resistance (hot)}}}.$$

EXAMPLE.—A coil has 450 sq. in. of surface, and a resistance (hot) of 15 ohms. It is required to know what is the largest current it can carry continuously without heating more than 30°F . above the surrounding air. Here the maximum current will be 3 amperes.

If we assume that a safe limit of temperature is 90°F . or 50°C . higher than the surrounding air, then the largest current which may be used with a given electromagnet is expressed by the formula

$$\text{Highest permissible amperes} = 0.95 \sqrt{\frac{s}{r}},$$

where s is the number of square inches of surface of the coils and r their resistance in ohms.

Similarly, for *shunt coils* we have

$$\text{Highest permissible volts} = 0.95 \sqrt{s r}.$$

The magnetizing power of a shunt coil, supplied at a given number of volts of pressure, is independent of its length, and depends only on its gauge, but the longer the wire the *less* will be the heat waste. On the contrary, when the condition of supply is with a constant number of amperes of current, the magnetizing power of a coil is independent of the gauge of the wire, and depends only on its length; but the larger the gauge the less will be the heat waste.

In running armatures the rise of temperature is relatively less owing to circulation of air; but the cooling effect of running is less in those machines that have their armatures almost entirely covered by the polar surfaces than in those in which the armature is more exposed. Owing to the cooling effect of the air-currents while running, it is found that when a dynamo is stopped at the end of a long run, the surface temperature immediately rises above what it was when running, as the heat which is being conducted outwards from the hotter interior is not now so rapidly got rid of. In the Admiralty specifications it is laid down that after the end of a long run of six hours, no part of the machine shall at the end of one minute after stopping show a greater rise than 30° F. ($=16.6^{\circ}$ C.) above the surrounding air. This is needlessly low; for ordinary engine-room work a rise two or three times as great is perfectly safe. Kapp allows 1.5 sq. inch ($=9.7$ sq. cm.) for each watt lost in the armature; and 2.5 sq. inches ($=16.2$ sq. cm.) per watt in the field-magnet. Esson finds that on armatures running at ordinary speeds, there will be a rise of 35° C. if for every watt wasted in heating 1.13 sq. inch ($=7.3$ sq. cm.) be allowed. The formula given above for field-magnets would show for the same rise a minimum surface of 1.5 sq. inch ($=9.7$ sq. cm.) per watt. Esson finds an approximate rule for different speeds to be

$$\theta^{\circ} \text{ (C.)} = \frac{55 w}{s (1 + 0.00018 v)};$$

where s is given in square inches, and v is the peripheral velocity in feet per second. If these are given in square centimetres, and metres per second respectively, the rule becomes

$$\theta^{\circ} (\text{C.}) = \frac{354 w}{s (1 + 0.0006 v)}.$$

From an elaborate study by Messrs. A. H. and C. E. Timmermann,¹ it appears that the number of watts that can be radiated per square inch per degree (C.) of rise of temperature increases with the speed, being about 0.010 at zero speed, 0.018 at a speed of 1000 feet per minute, and 0.022 at 3000 feet per minute. For a temperature rise of 30° C. the number of square inches of radiating surface per watt is about 3.3 at zero speed, about 1.9 at 1000 feet per minute, and about 1.5 at 3000 feet per minute.

Some calculations about the greater heating of interior layers have been given by Mr. Joyce.²

The following rules are useful for calculating the windings for machines of same type, but of varying size, or output.

To reach the same limiting temperature with equal-sized bobbins wound with different-sized wire, the cross-section of the wire must vary as the current it is to carry; or in other words, the current density (amperes per square centimetre) must remain constant.

To raise to the same temperature two similarly shaped coils, differing in size only, and having the gauge of the wire in the same ratio (so that there are the same number of turns on the large coil as on the small one), the currents must be such that the squares of the currents are proportional to the cubes of the linear dimensions.

Similar iron cores, similarly wound with lengths of wire proportional to the squares of their linear dimensions, will when excited with equal currents, produce equal magnetic forces at points similarly situated with respect to them. (Lord Kelvin, *Phil. Trans.*, 1856.)

¹ *Trans. Amer. Inst. Electr. Engineers*, x. 1893.

² *Journ. Inst. Electr. Engineers*, xix. 248, 1890.

Similar machines, if magnetized to an equal degree of saturation, must have ampere-turns proportional to the linear dimensions.

If two machines are to give same electromotive-force, the diameter of the wire of the coils must vary as the linear dimensions.

If, in altering the field-magnets of a machine of any given capacity, the lengths of the several portions of the magnetic circuit remain the same, but the several areas are altered, then the wire for rewinding must have its cross-sectional area altered in proportion to the periphery of the section of the cores.

The resistance of a coil, the volume of which is known, and which is wound with (round) copper wire of diameter d millimetres, enlarged by insulation to a diameter of D millimetres, can be calculated by the following rule, which is based on the assumption that the partial bedding of the convolutions allows of 10 per cent. more wires being got in than would be the case if they were exactly wound in square order. This figure can only be approximate, as the amount of bedding varies somewhat with the relative thickness and pliability of the coating of insulating materials, as well as with the gauge of the wire. If v be the volume in cubic centimetres, the resistance r of the coil in ohms (cold) would be

$$r = 0.0244 \frac{v}{D^2 d^2}.$$

If v be expressed in cubic inches, and D and d in mils (1 mil = .001 inch), then the approximate formula becomes

$$r = 960,700 \frac{v}{D^2 d^2}.$$

LENGTH AND DIAMETER OF ARMATURES.

Various rules have been given for the ratio between the length, L , of an armature-core and its diameter, d , embodying the results of practice.

In the case of 2-pole dynamos the usual dimensions for

TYPICAL ELECTRIC MACHINERY.

For machines of the type $L = \frac{1}{2} d$ to $L = 1\frac{1}{2} d$; $L = d$ being the most frequent. For square forms $L = 2 d$ is frequent, though the ratios $L = \frac{3}{2} d$ and $L = \frac{1}{2} d$ are also found. In the Edison system for machines L varies from 1.85 to 1.9 d in the case of 2 to 5 poles. For multipolar machines the diameter is usually greater than the length. In Brown's case (see Page VIII and Fig. 244) $d = 2 L$ nearly.

SECTIONS OF FIELD-MAGNETS.

A comparison of the machines of various makers shows that for the machines the usual practice is to allow for magnetising the machines a cross-section 1.45 times that of the material as it is wrought with it mild cast steel; or 3 times, if the magnetising is of cast iron. For the magnet-cores of arm machines the usual figures are 1.25 and 2.3.

The question sometimes arises what is the best *shape* of section for the magnet-cores. This point is readily answered by considering the geometrical fact that of all possible forms enclosing an area the one with least periphery is the circle. The following summary in the following table exhibits the relative weights of various required to wind round various forms of section enclosing equal area. The area of the simple circular form being taken as unity, and allowance made for thickness of winding —

Circle	3.54
Square	4.00
Rectangle, 3:1	4.24
Rectangle, 4:1	4.62
Rectangle, 5:1	6.91
Circle made of the square between two semicircles	3.76
Circle made of two squares between two semicircles	4.28
Two circles side by side	4.997
Two circles, but with wind round both together	4.10
Three circles " " " each separately	6.13
Four circles " " " " "	7.09

Symmetry of Field-magnets.—It was pointed out on p. 167, that in 2-pole single-circuit field-magnets the field is unsym-

metrical, being much stronger between the inner horns than between the outer horns of the pole-pieces, if the poles are shaped away as in Fig. 100, No. 23. Such shaping produces several evil results. Firstly, the armature is attracted downwards as a whole (see p. 327); secondly, the armature, if ring-wound, will be electrically out of balance, owing to the unequal magnetic field at opposite ends of a diameter; thirdly, the neutral points for non-sparking will not be at opposite ends of a diameter.

Effect of Widening the Gap-space.—The effect of widening the gap-space is in every case to necessitate more ampere-turns of excitation. It also has some other results. It slightly increases the leakage coefficient v . It enables thicker copper

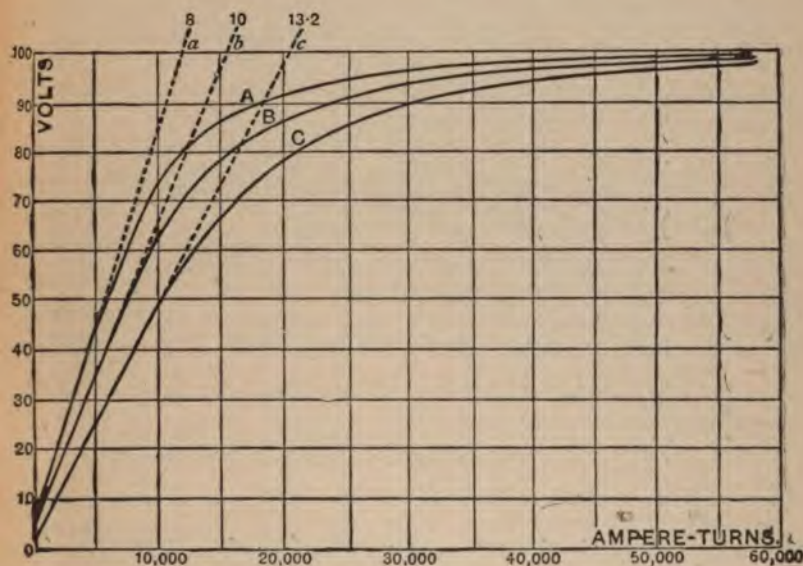


FIG. 260.—EXCITATION NEEDED WITH DIFFERENT GAP-SPACES.

conductors to be wound on the armature, diminishing its internal resistance; and, if the armature has not been loaded beyond the safe point of sparklessness, increases the output of the machine. It has the further not unimportant result of increasing the reluctance in the path of the cross-magnetizing

magnetomotive-forces, and diminishes their prejudicial action. Some ideas as to the first of these effects may be gathered from considering the curves given by Arnoux, in Fig. 260, showing the result of widening a gap-space from 8 to 10, and then to 13.2 millimetres. The initial slopes of the curves are given by lines whose tangents are inversely proportional to the gaps. It will be noted that in their upper part the three lines approach one another.

INTERFERENCE OF ARMATURE FIELD.

As explained in Chapter IV., p. 71, the armature-current tends to cross-magnetize, and if the brushes have a forward lead (or in a motor a backward lead) tends also to demagnetize the field. We saw on p. 80 that the position of the

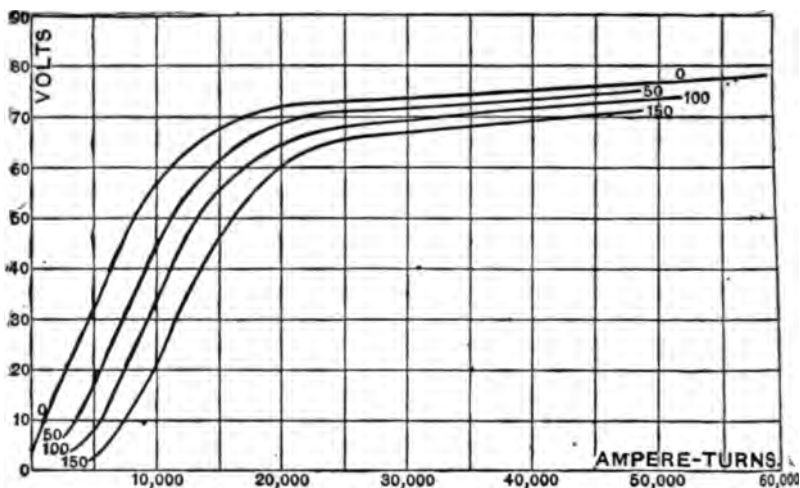


FIG. 261.—LOAD-CURVES OF A DYNAMO.

neutral point for non-sparking is affected by this interference: and on p. 353 we learned how to compensate the demagnetizing effect. We have now to consider the matter further from the point of view of dynamo design.

In the first place, let us examine the behavior of some

existing dynamo, by observing the relation between its voltage and the amount of excitation, at some constant speed, under varying conditions of load. Let the lead given to the brushes be varied as required to fulfil the condition of sparklessness. First let a curve be found with zero armature current; then with a 50-ampere load, then with 100 amperes, and so forth. The experiments should be made in each case by beginning with the highest excitation (and smallest angle of lead) and gradually diminishing the excitation (and increasing the lead) until a sparkless position can no longer be found for the brushes. This dynamo¹ was intended for a normal output of 150 amperes at 70 volts. It will be found that in each case, the smaller the load the more may the excitation of the field be diminished before the state of things is reached that no neutral point can be found. In other words, there will always be some definite relation between the ampere-turns on the armature, and those on the field-magnet which fixes the working limit of sparklessness. We shall presently inquire into this relation. For the present it may be remarked that these load-curves² give us much information as to the necessary windings of the field-magnet, how many ampere-turns must be contributed on open circuit by the shunt coil, and how many compensating ampere-turns must be added by the series coil in order to keep up the voltage.

Limits of Load and Non-sparking Point.—Two things limit the output of a dynamo: the heating of its armature conductors, and sparking at the brushes. Given a dynamo, if by widening the gap a little and rewinding its armature with copper wire of double cross-section, we reduce its resistance to one-half, we may then take from it nearly a double current with no more heating than before, provided it still does not spark. Such a reconstituted machine would clearly cost less than two of the previous pattern. But the limit of such an augmentation of the output by increasing the ampere-turns on

¹ See Arnoux in *Bull. de la Soc. Int. des Électriciens*, vi. 61, 1889.

² For other examples of load-curves see Esson in *Journal Instit. Electrical Engineers*, xix. 152, 1890; and Kapp, in *Proc. Instit. Civil Eng.*, Feb. 1889.

the armature is reached very soon; for the cross-magnetizing tendency is doubled, and the lead increased, and the demagnetizing tendency more than doubled by doubling the ampere-turns of the armature. These perturbing effects may be all included under the general name of *interference* used in the previous paragraph: they have been investigated more or less fully by Hopkinson,¹ and more completely by Swinburne,² and by Esson.³

It has been pointed out on p. 79, that because the windings of the armature possess self-induction, the reversal of the current in them in the act of commutation as they pass the brush requires the presence of an impressed electromotive force; and that this is accomplished by giving the brush a lead (forward in a dynamo, backward in a motor) so that that section in which the current is to be reversed is at that time passing through the fringe of the magnetic field. The stronger the current to be reversed, the stronger is the field necessary for sparkless reversal. But the field under the "trailing" horn of a pole-piece (or in a motor, the "leading" horn), near which commutation must take place is, as we have seen (Figs. 62 and 66), weakened by the interference of the armature. Now the cross-magnetizing action of the armature tends to send magnetic lines up (see usual diagram Fig. 61, p. 73) both sides of the ring core, which tend to cross the gaps and return through the masses of the pole-pieces; the strongest cross-magnetizing force in the gaps being under the tips of the polar horns. This cross action opposes the normal flux of magnetic lines at the top right and bottom left corners (of Fig. 63), and helps it at the other two. The cross-magnetizing magnetomotive-force under the pole-tips (assuming the gaps alone to offer any appreciable reluctance) is equal to $\frac{A}{10} \pi$ times the ampere-turns of all the conductors that lie in the

¹ *Philosophical Transactions*, 1866, pt. i. p. 331; and *Electrician*, xviii., Dec. 1866.

² *Journal Instit. Electrical Engineers*, xv. p. 540, 1886; and xix. pp. 90 and 265, 1890.

³ *Ib.*, xix. p. 118, 1890; and xx. p. 265, 1891; also *Electrical World*, xv. 213, 1890; see also *Electrical Review*, series of articles on Synthetic Study of Dynamos, 1890.

gaps, or within the angle of polar span ψ . Using the usual symbols— Z for the number of conductors around the armature, and C_a for total armature current—we have for the total ampere-turns on the armature $\frac{1}{2} Z \times \frac{1}{2} C_a$ of which $\psi \div 180^\circ$ are effective, and of which the half may be taken as the part operative in either place where the cross-circuit crosses a gap. If ψ is taken at 120° , the cross-force under the tip will be

$$\frac{1}{2} Z \times \frac{1}{2} C_a \times \frac{1}{2} \times \frac{1}{10} \pi \times \frac{120}{180} = C_a Z \times 0.104;$$

or equals the ampere-turns¹ on the armature multiplied by 0.416. Now let us see what number of ampere-turns on the armature would produce a cross-force in the gap just exactly balancing the normal magnetizing force there, so as to neutralize the field under the pole-tip. In that case sparkless reversal would be impossible, and so we should have ascertained the limit of load. Now the difference of magnetic potential in the gap (or that part of the magnetomotive-force that is spent therein) is equal to the product of the magnetic reluctance of the gap into the flux across it. If l_2 be the length across the gap and A_2 the polar area, the reluctance of the gap is $l_2 \div A_2$, and the magnetic potential-difference in it is $= N l_2 \div A_2$. Now call the length of the armature core or of the pole-face, parallel to the axis, L ; the breadth of the pole-face measured along the curve from tip to tip b ; the radial depth of the core r ; and its sectional area A_1 . We may assume that in the core the magnetization is pushed to $B = 17,000$. Then we have the following relations:—

$$N = 17,000 A_1; A_1 = r L; A_2 = b L.$$

¹ This term is here used precisely as for any electromagnet. In bipolar drum-armatures it is half the armature current multiplied by half the number of external conductors. In multipolar machines (wound with parallel grouping) it is equal to total current multiplied by total number of conductors and divided by the square of the number of poles. In Esson's paper of 1890 (*Journal I.E.E.* xix. 143), the term ampere-turns was used in a different sense, namely, as the product of the total number of conductors into the current carried by each. This is the same thing to which in his paper of 1891 (*Journal I.E.E.*, xx. 266) he gave the not very apposite name of "volume," but which would have been better described as the total circulation of armature current. The name used hereafter for this quantity is the *circumflux*. For 2-pole machines the circumflux is twice the ampere-turns; for 4-pole machines, four times, &c.

Substituting these in the preceding expression, and cancelling out L , we get

Magnetic potential in gap = $17,000 \times r \times l_2 \div b$.

Equating this to the cross-force, we get

$$\frac{C_a Z}{4} = \frac{40900 \, r l_2}{b}$$

For some purposes it is more convenient—particularly in relation to the multipolar machines—to consider not the ampere-turns of the armature, but the effective circulation of current as reckoned by multiplying together the number of armature conductors and the current carried by each independently of its direction. This quantity, here denoted by the symbol Q , we shall call the *circumflux*.¹ It is equal to the product of the whole armature current, into the whole number of armature conductors, divided by the number of poles. For a 2-pole dynamo we then have as the limiting load on the armature

$$Q = \frac{C_a Z}{2} = \frac{81800 \, r l_2}{b}$$

Esson² gives the result of observation of a number of modern dynamos by different makers, and found the actual numerical coefficient to vary from 61,265 to 95,905 for ring machines, with a mean of 85,000, differing little from the theoretical 81,800 given above.

From the foregoing it appears that the maximum load which an armature can carry, within the limit of sparklessness, is directly proportional to the radial depth of core, and to the length of the gap, but inversely proportional to the breadth of the polar span. If, therefore, taking an existing machine whose load is just within the spark limit, we wish to make it carry a heavier load (or more copper on the armature) we may do so either by increasing the radial depth of the core-disks, or by increasing the gap-space (whether wanted for copper

¹ Called by Esson at one time the "ampere-turns," and later the "volume," of the armature current. See preceding footnote.

² *Journal I.E.E.*, xx, 142, 1890.

and clearance or not), or lastly, by diminishing the breadth of span of the polar faces. The first of these causes means a new armature; the second requires the pole-faces to be bored out afresh, and also means some (not large) addition to the magnetizing power of the field-magnet; the third has the effect of concentrating the magnetic flux, therefore, lowering slightly the permeability, and necessitating either a slightly higher speed or a slight increase in the magnetizing power.

The circumflux or polar circulation of armature current permissible for an armature of given diameter may be given in terms of the diameter by assuming (for ring 2-pole armatures) that $b = 1.05 d$; $r = 0.1 d$; and $l_1 = 0.05 d$.

Substituting these values, we get

$$Q = 390 d.$$

Esson takes 400 d (centimetres) as the limiting value of Q , for rings, and 600 d as the value for drums. Kapp allows 1000 ampere-turns (or 2000 circumflux in case of 2-pole machine) for each inch of diameter above 12 inches, as a safe load.

We are now ready to consider the safe output (watts) of a dynamo in terms of its dimensions.

The gross output of a bipolar dynamo is—

$$W = E C_a = n N Z C_a \div 10^8; \quad (\text{see p. 170})$$

or for a multipolar dynamo—

$$W = n N \frac{CS}{p} \div 10^8;$$

where p stands for the number of *pairs* of poles: so that the value of Q , the circumflux of armature current, will be $ZC_a \div 2p$; whence

$$W = 2 n N \times Q \div 10^8. \quad [a]$$

Now assume (as fair average of actual cases) that pole-pieces together cover $\frac{7}{10}$ of circumference (or $2.2 \times d$), and that the value of B in the gap is 5000. Then, if L is length of armature core (cms.), the working area of the armature

through which magnetic lines go in or out $= 2.2 \times d \times L$; whence area of any one polar part is $2.2 d \times L \div 2 p$; and the flux of magnetic lines through any one pole will be 5000 times this; or for the total flux through the $2 p$ poles will be

$$N = p \times 5000 \times 2.2 d \times L \div 2 p = 5500 d \times L.$$

Inserting this value we have—

$$W = 11000 \times d + L \times n \times Q \div 10^8 \quad [5]$$

But, according to Esson, as above, $Q = 400 d$ for rings or $600 d$ for drums as the safe loads. Inserting these values we get¹—

$$\left\{ \begin{array}{l} \text{for rings } W = d^2 L n \times 0.044 \\ \text{for drums } W = d^2 L n \times 0.066 \end{array} \right\} \quad [7]$$

Now $d^2 L$ is proportional to the volume of the armature core. Hence we conclude that the output is proportional to volume and to speed, and is independent of the number of poles and of the grouping of the armature conductors. Kapp finds it (for equal surface temperature) to increase as the $3\frac{1}{2}$ power of the diameter. This is a slightly higher proportion than the volume, probably because of the somewhat higher peripheral speeds admissible for large armatures.

DEVICES FOR COMPENSATING ARMATURE REACTION.

As the output of a dynamo is limited both by heating and by sparking, the designer must consider very closely how the latter can be abolished. There are many cases in which a dynamo or motor might be called upon to give double its normal output for a few minutes. Double output means quadruple heating, which if continued for only a short time may do no harm; whereas if sparking were to continue at the commutator for an equal time serious damage might be done. It is therefore important to so design machines that even

¹ Esson, taking slightly greater width of pole-pieces, gets 0.048 and 0.072 as the respective co-efficients. Snell (*Journal I. E. E.*, xx. p. 197) finds his machines give as their co-efficients, when translated into centimetres and seconds to correspond, 0.0375 and 0.056 respectively.

with double load they will not spark at the commutator. We have seen how the limit at which sparking begins depends upon the armature reaction, interfering with the field in the neighbourhood of the pole-tips, where it is needed for procuring sparkless reversal.

Consider first the theory¹ of armature interference. Draw any closed curve A B C A along the magnetic circuit (Fig. 262) so that it passes through the magnetizing coils. The line integral of the magnetizing forces along this line will be equal (see p. 118) to 0.4π times the ampere-turns in the coils. There will be an equal magnetomotive-force around the closed curve D E F D, though the resulting flux along this path may be less,

owing to the greater reluctance. Similarly if the brushes are advanced with an angular lead λ , the number of conductors in the demagnetizing zone (see p. 85) will be a fraction $2\lambda \div \pi$ of the whole number Z on the armature, and as each carries half the current, the demagnetizing ampere-turns (for drum-winding) will be

$$\frac{1}{2} C_a \times \frac{1}{2} Z \times 2\lambda \div \pi = \lambda C_a Z \div 2\pi,$$

and the demagnetizing magnetomotive-force will be $0.2\lambda C_a Z$. Further, the tendency to cross-magnetize may be calculated by considering the closed curve H A G D H drawn through the pole-tips of one pole-piece. If the angle of polar span be called ψ , the number of conductors enclosed by this curve will be $\psi Z / 2\pi$, and the line-integral of the cross-magnetizing forces will be $0.4\pi \times \frac{1}{2} C_a \times \psi Z / 2\pi = 0.1\psi C_a Z$. As the reluctance in the parts of this path which pass through iron is

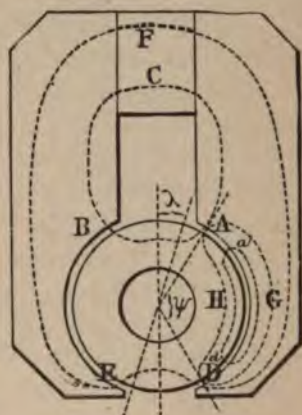


FIG. 262.

ARMATURE INTERFERENCE.

¹ Drs. J. and E. Hopkinson, *Phil. Trans.*, 1886; also reprint of Hopkinson's *Original Papers*, 1893, 105.

negligible, we may regard the whole of this as expended on the gaps at A and D: and it will be seen that the difference of magnetic potential at the gap A will be diminished, and that at D increased, by half this amount. Since any smaller closed curve, as at δ , encloses fewer conductors, it will produce a proportionately smaller distorting effect. The minimum field required for reversal in the neighbourhood of the pole-tip depends both on the current to be reversed, on the self-induction of the δ -section, and on the time occupied in the act of commutation. The cross-force which tends to diminish the field at the region A must not be suffered to reduce the field below the necessary minimum. It will be noted that the demagnetizing reaction (which is proportional to δ) tends to weaken the field in general, while the cross-magnetizing reaction tends (which is proportional to ϕ) to weaken the field under the leading pole-tips, and to strengthen it under the trailing tips. In order that we may be able to reverse sparklessly very great currents, we must have the impressed field so strong that at least the minimum field remains at the pole-tip in spite of both these reactions. Seeing, then, that the cross-field is responsible for the distortion which makes sparkless collection difficult, it remains to consider the remedies. These may be classified under two heads—those applied to the magnets, and those applied to the armature. The former class may again be sub-classified: for in dealing with the cross-field we have two courses open, either to increase the reluctance in the path or to introduce a compensating counter cross magnetomotive-force.

Cross-Reluctance Remedies.—Any gap introduced across the closed path H A G D H of the cross forces will diminish the cross-field; hence merely widening the clearance or the armature will to some extent help; but then more winding will be wanted on the magnet-cores. The polar mass behind the face may be nearly divided by a “V” groove; as is readily done in the case of magnets of the Manchester type (No. 24, Fig. 101) and other forms having double magnetic circuits (as No. 8, Fig. 100 and Fig. 109) by judicious thinning or by equal separation, as in No. 27, Fig. 101, between the right

and left-hand halves, and so throttle the cross-flux of magnetic lines. To prevent weakening of the structure a thin web is

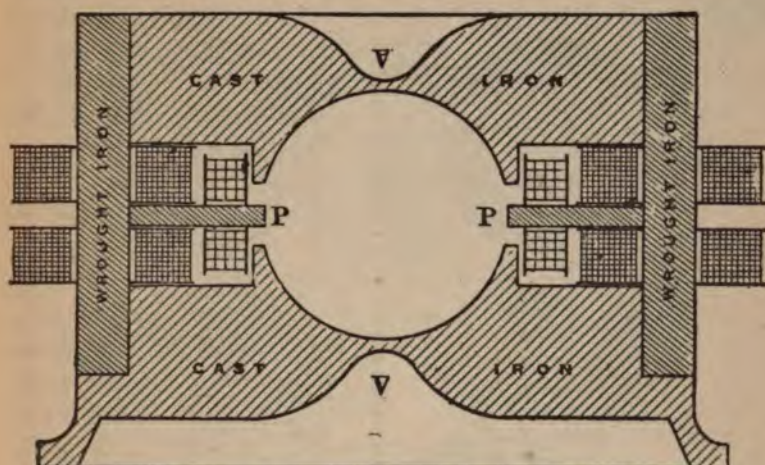


FIG. 263.—MAGNET WITH V-GAPS AND COMPENSATING POLES.

left in the casting, as in Fig. 263. Another suggestion, made by the author of this work some years ago, was to construct the field-magnets of pieces of iron with longitudinal gaps, as in Fig. 264.



FIG. 264.

Cross-Compounding Remedies.—

Elihu Thompson proposed to place a compounding coil on a separate frame surrounding the armature, and to tilt it in a direction counter

to the rotation so as partially to counteract the cross force. Swinburne¹ suggested that a small auxiliary coil (in series) should be wound upon the tip of the pole, as in Fig. 265a, to maintain a reversing field at that point. Mather,² Housman,³ and Swinburne⁴ have all advocated the use of auxiliary poles

¹ *Journ. Soc. Teleg. Engineers*, xv. 542, 1886.

² *La Lumière Électrique*, xix. 404, 1885.

³ *Journ. Inst. El. Engineers*, xx. 299, 1891.

⁴ See Swinburne (*Journal I.E.E.*, xxx. 105, 1890); and Housman (*ib.*, xx. 299, 1891), who maintains that if $B = 7000$ under the pole-piece, the auxiliary field for reversing must be at least $= 3000$.

at right-angles to the main poles (as in Fig. 263), wound with main circuit coils to counteract the armature force. The

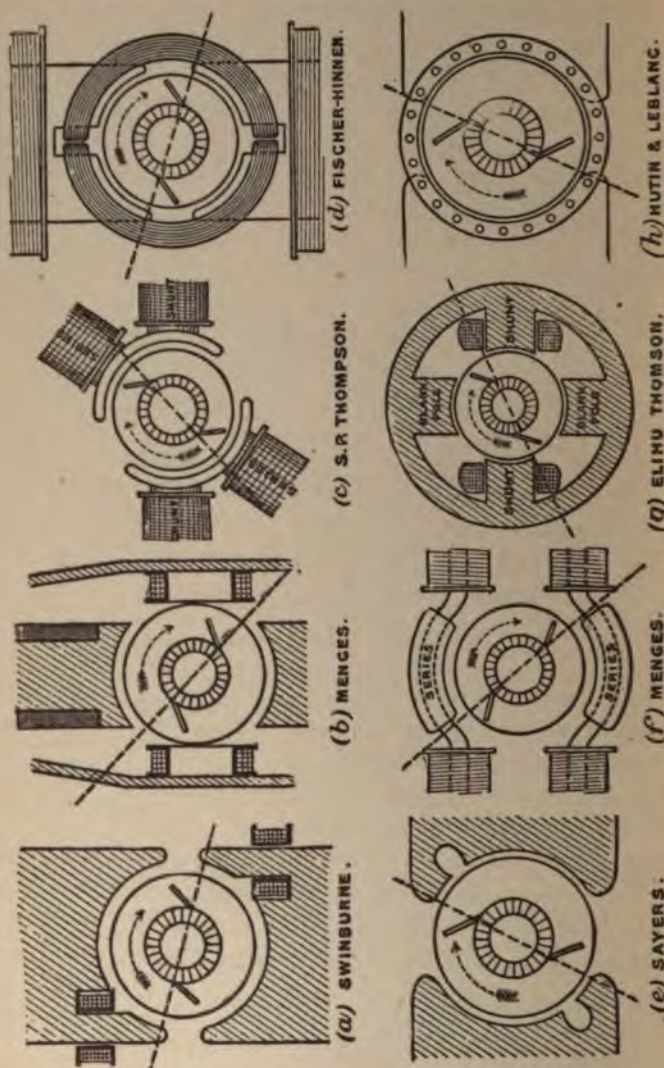


FIG. 205—VARIOUS DEVICES FOR SPARKLESS COLLECTION OF CURRENT.

author of this treatise suggested a sort of compound winding having series and shunt poles at different angles (Fig. 265c)

so that as the armature reaction tended to shift the field forward, the field should automatically shift itself back. Menges,¹ in 1884, proposed a cross-compound winding having the auxiliary series coils set to produce a field at right angles (Fig. 265*b*) to the ordinary field. He also suggested winding series coils around the polar parts of a machine with double magnetic circuit, as in Fig. 265*f*. Fischer-Hinnen² winds these coils in a notch at the centre of the pole-face (Fig. 265*d*), a construction which independently occurred to Prof. Forbes, to Mr. Mordey, and the author.

Prof. Elihu Thomson³ has lately proposed another solution (Fig. 265*g*), in which, by the use of auxiliary unwound poles presented, at right-angles, to the armature, he leads off the

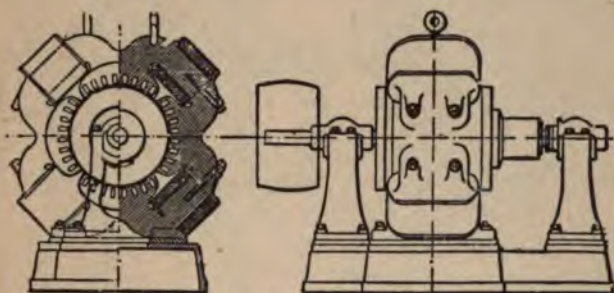


FIG. 266.—RYAN'S DYNAMO, WITH CROSS-COMPOUND COILS.

cross-flux into the back of the wound poles, and uses it to strengthen the field, instead of weakening it.

The most complete solution, however, is that given by Prof. Ryan,⁴ who inserts a number of coils in slots cut in the pole-face parallel to the shaft, to receive a series winding, which thus constitutes approximately a neutralizing layer of coils with a circulation of current equal and opposite to that of the armature. Fig. 266 shows a recent design of Ryan's

¹ D. R. P. No. 34,465.

² *Berechnung elektrischer Gleichstrom-maschinen* (Zürich, 1892).

³ *Electrical Review* (N. Y.), xxvii. 18, July 1895.

⁴ "On a Method of Balancing Armature Reaction," *Sibley Journal of Engineering*, vii. 17, Oct. 1892; see also Ryan and M. E. Thompson, *Am. Inst. of Electrical Engineers*, 1895, where tests are given of such machines; reprinted in *Electrician*, xxxiv. 765, April 19, 1895.

with the coils arranged in slots. In such machines the magnetization does not drop with the load, nor does the neutral point shift. Further, the gap-space may be made very small, reducing the weight of the field windings. The entire absence of distortion of field at all loads is a gain; but for absolutely sparkless collection it seems better to provide a special commuting field than to depend on finding one somewhere in the fringe near the pole-tip. This Ryan proposes to accomplish as shown in Fig. 267 by bridging the space between the poles C D by an iron structure, slotted at *k l m o p*, to receive the

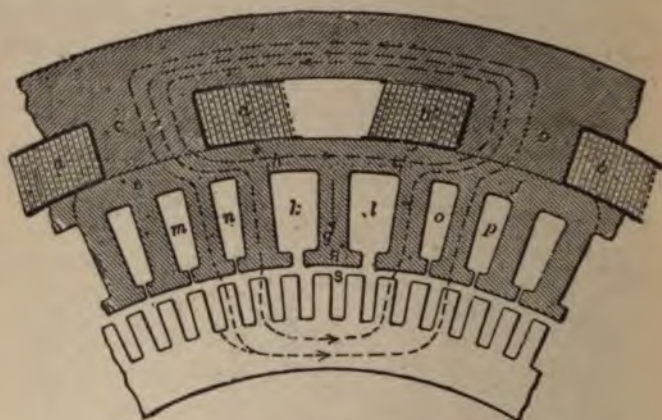


FIG. 267.—RYAN'S COMPENSATING DEVICES.

compensating conductors, and provided with a special commuting lug *g* in the centre of these windings. At no load this lug is not magnetized; but as load increases the excess of ampere-turns in these compensating windings over the cross ampere-turns of the armature tends to magnetize *g* in the direction of the arrow, giving a commuting field always proportional to the current to be commutated.

Finally MM. Hutin and Leblanc have proposed to deaden sparking by use of a device called an *ammortisseur*, consisting of a series of rods of copper carried through slots in the pole-faces all short-circuited together at their ends by being united to two rings of copper, constituting an embedded squirrel-cage.

This device (Fig. 265h) is supposed to prevent oscillations in the direction of the magnetic flux which occur at commutation.

Concentration of Field.—There are other methods of preserving the requisite concentration of field at the leading edge of the pole. It is obviously desirable that the field should be magnetically *rigid*—not easily distorted. This stiffness of field can be partially secured by judicious shaping of pole-pieces. A simple notch in the pole-face, as in Fig. 265e, promotes concentration of the field in the tip. If the tip is itself nearly saturated, the tendency to distortion may produce

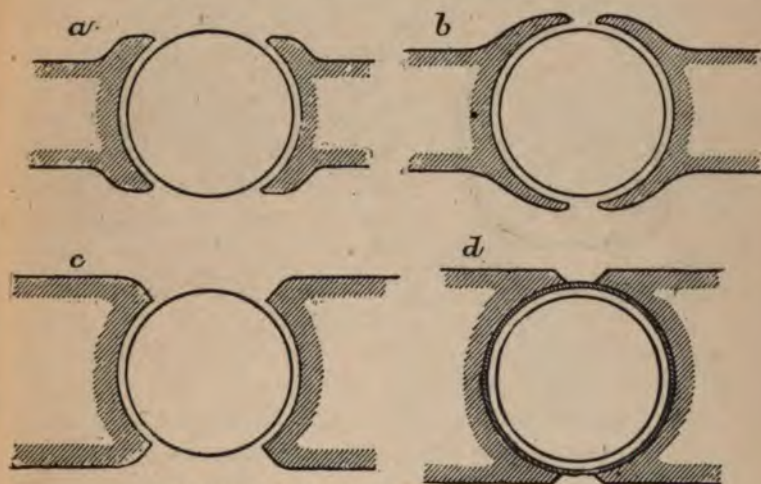


FIG. 268.—VARIOUS FORMS OF POLE-TIPS.

less effect than if it were far from saturation. But it is not on this account worth while to make the tips of cast iron instead of wrought, as they then saturate with a less flux. Tips widely separated, like Fig. 268a, are not always good, even though thin. It is better that they should either be extended like Fig. 268b, nearly to meet, so that they may be saturated by the leakage field, or else cut off like Fig. 268c. Dobrowolsky has recommended the *bushed pole* (Fig. 268d), in which the armature is completely surrounded with iron.

These forms differ very greatly as to the width of *fringe* which they permit in the field. It is of advantage that the field

should present, where the conductors enter, a margin in which the flux-density varies from zero to a high value. If this margin is too narrow, the neutral point will be very well defined, and the brushes need very accurate adjustment. If it is too wide, the variations of lead at different loads may be excessive. One way of securing a suitable fringe, and at the same time maintain fair rigidity against distortion, is to bore the polar faces to a different and flatter curve, so that the polar gap is narrowest at the middle and wider at entrance and exit, as in Fig. 269. Another way, which has been found

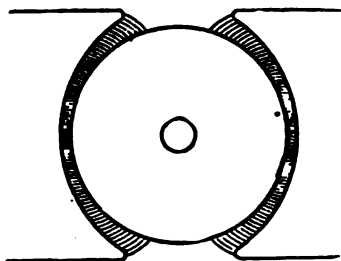


FIG. 269.—NON-CONCENTRIC POLES.

excellent by Mr. Brown, for his well-known 4-pole machines (Fig. 276), is to make the inwardly projecting poles of circular section, without any pole-shoes or extensions. The end-face of the pole when bored away presents a sufficient lip, and secures a well-gradated field of sufficient stiffness.

Self-compensating Armatures. — Turning to armature methods of compensation, we find several devices. Swinburne's chord winding (p. 246) diminishes the demagnetizing but not the cross-magnetizing force. It has the disadvantage that the two edges of any section are not both passing at the same instant into a commutating field; hence it is not good for handling large outputs in machines with small clearance. Its service is to give a machine which up to its spark-limit has so little demagnetizing reaction that the excitation does not require to be increased to keep up the pressure as the load increases. Edison¹ has proposed an auxiliary winding, and also other devices involving the use of two sets of brushes at different leads.

The best suggestions are those of Sayers,² who connects the bars of his commutator to the appropriate point on the

¹ Specification of British patent, No. 5127 of 1888.

² *Inst. Elec. Eng.*, July, 1893, xxii. 377; 1895, xxiv. 122.

ring or drum winding, not directly in the ordinary way by radial connectors, but through auxiliary compensating coils wound also upon the armature. One of these *commutator coils* is shown in Fig. 270, one end being attached to the junction between two main armature coils and the other end being attached to a commutator bar. At the instant before the bar comes in contact with the brush the whole armature current is being carried by a commutator coil immediately

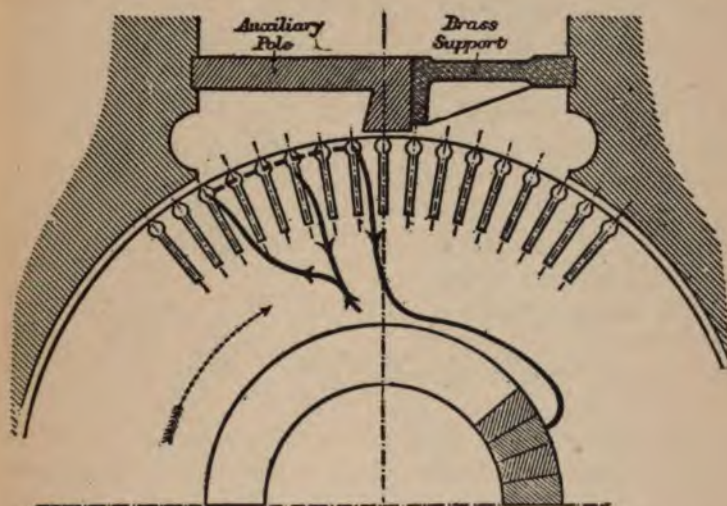


FIG. 270.—SAYERS' COMPENSATING WINDING WITH COMMUTATOR COILS.

ahead of the one shown in the figure. When the heel of the brush touches the bar, the left side of the commutator coil belonging to it is well under the pole-piece, so that it tends to take up the current ; while the commntator coil preceding it has its right side just coming under the auxiliary pole, tending to stop the current in it and reverse it in the intermediate main armature winding. The commutator coil in Fig. 270 has just taken up the current. A moment later its right side will come under the auxiliary pole, which will stop the current in it and pass it on to the next commutator coil. Sometimes the auxiliary pole is wound as shown in Fig. 263. The main advantage of Sayers' winding is that instead of

putting the brushes forward, he is able to give them a *backward lead*, so that the armature current exercises a helpful magnetizing action, and obviates the need of any compound winding on the field-magnets. (See also p. 438 and Plate XII.)

DESIGN OF MULTIPOLAR DYNAMOS.

Bipolar machines are common for small dynamos, but for large outputs multipolar are preferred.

The advantage of using Q (the circumflux) rather than the ampere-turns, in the investigation on pp. 384 and 385, was that the spark limit of load depends not on the total ampere-turns or action of the whole armature as an electro-magnet, but on the circulation of current per pole. Hence the results already obtained are available for multipolar machines, as was pointed out by Esson, to whom is due the credit of this conception.

The second formula on p. 384 may now be re-written—

$$Q = \frac{577 B l_2}{\phi};$$

where B is the strength of field in the gap-space.

If we assume the limiting values of Q , and the usual value of B , as already determined, then if ϕ , the angle of polar span, be taken at 130° , it follows that the radial depth l_2 of the gap-space must not be less than $\frac{1}{2}d$, for rings, nor less than $\frac{1}{8}d$, for drums. Then, if in order to make a large output machine, whilst keeping to two poles, we increase d , we must either increase l_2 or B , or else diminish ϕ , or perform some combination of these processes, which in any case involves a greater expenditure of power in maintaining the field in the gap-space. Herein lies the advantage of multipolar construction for large outputs. Consider such a form as Fig. 271 with 4 poles. To prevent undue leakage from pole to pole the distance between pole horns is wider relatively to the polar span than in a 2-pole machine; and, for an equally high value of B in the gap-spaces, the section of the ring is reduced, its diameter enlarged, and with its diameter its cooling surface.

For drum-wound machines there is, in addition to such gains, the additional advantages that end-connections are much simpler, and ventilation easier, than for 2-pole machines. But does it pay the constructor to make the change? There is a little more labor in tooling castings; but will he save copper? A case will show that, beyond a certain limit of size, there is a saving. Consider a 2-pole drum; $d = 50$; $L = 90$; $B = 5000$ in the gap; $\psi = 130^\circ$. Then it will not be sparkless unless the gap-space l_2 is at least 3.2 cm., or about

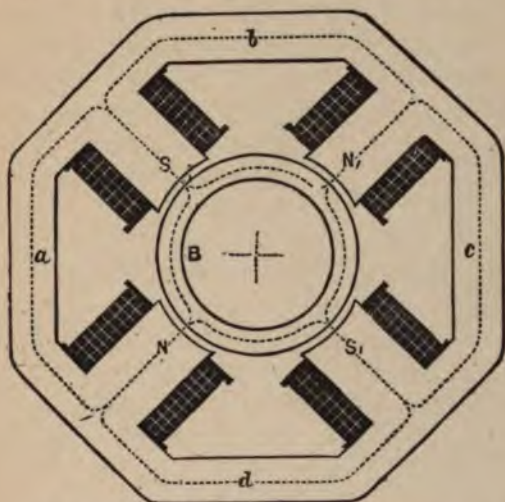


FIG. 271.—FOUR-POLE MAGNET (BROWN).

0.9 cm. more than is needed for windings and clearance. If, to make this work sparklessly, we diminish the gap and increase B to 7000 or diminish ψ to 100° , we still gain nothing in magnetizing power. Now substitute a 4-pole drum: $d = 84$; $L = 45$; $B = 5000$. With this increased diameter, the gap-space may be reduced to a maximum, the magnetizing power may be reduced by at least 30 per cent., and the total weight of iron by nearly 40 per cent., which will more than pay for the extra labor of tooling. Esson states that the cost of a 4-pole dynamo, of output W at speed n , may be put as being equal to that of two dynamos, each of out-

put $\frac{1}{2}$ W at speed $2n$, and so forth. The cost of field-magnet castings is reduced, and their weight lessened, when, as in the large machines of Siemens and Halske (Plate VIII.), the ring is of such large dimensions that the field-magnet can be placed internally.

For machines exceeding 100 kilowatts multipolar forms are, then, generally preferable to bipolar; firstly, because they give their maximum sparkless output with minimum clearance, and therefore with minimum weight of copper on magnet; secondly, because they keep cooler, so that for a given volume of core and winding there is actually a greater output. Multipolar machines have one further advantage over bipolar machines, in that their length may be shortened relatively to the diameter without loss in economy, and with great mechanical gain. In the case of drum windings this is very marked.

BEST THICKNESS OF GAP-SPACE.

Professors Ayrton and Perry have investigated¹ the rule for the best thickness of the conductors on armatures. By finding an expression for the total heat-waste in terms which included the heat wasted in the excitation needed for the different parts of the reluctance, and considering what relations between these would make this waste a minimum, they came to the following conclusion:—The permissible continuous output of the machine is a maximum when the thickness of the winding on the armature is such that *the magnetic reluctance of the space occupied by the winding on the armature is equal to the reluctance of the rest of the magnetic circuit.*

Assuming that practically the whole of the gap-space between armature-core and pole-piece is filled with armature winding, the above rule amounts to saying that, given the construction of armature, the dynamo ought to be worked at such a degree of excitation that its total magnetic reluctance is run up to be twice as great as that of the gap-space alone. This is indeed no other than the diacritical stage of magnetization, the permeability in gross of the magnetic circuit—iron and air together—being at this point reduced to half its initial value.

¹ See their paper, *Phil. Mag.* for June 1888; or page 444 of the fourth edition (1892) of this work.



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